# Globally Significant Mass of Terrestrial Organic Carbon Efficiently Transported by Canyon-Flushing Turbidity Currents

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**ABSTRACT**

Burial of organic carbon in marine sediments is a long-term sink of atmospheric $CO_2$ and submarine turbidity currents are volumetrically the most important sediment transport process on Earth. Yet the processes, amounts, and efficiency of organic carbon transfer by turbidity currents through submarine canyons to the deep sea are poorly documented and understood. We present an organic carbon budget for the submarine Congo Canyon constrained with time-lapse bathymetry, sediment cores and flow monitoring, including the effects of two >1,000 km runout

canyon-flushing turbidity currents. In one year, flows eroded an estimated 6.09 ± 2.70 Mt of previously-buried terrestrial organic carbon in the canyon, primarily from fine-grained and vegetation-rich muddy sand facies with high organic carbon contents (up to 11%). The age and composition of organic carbon in the Congo Canyon is comparable to that in the Congo River, indicating that transfer is efficient. Over the whole canyon-channel system, we extrapolate that 43 ± 15 Mt of organic carbon was eroded and transported to the deep (> 5 km) sea, equivalent to 22% of the annual global particulate organic carbon export from rivers to oceans, and 54-108% of the predicted annual terrestrial organic carbon burial in the oceans. Canyon-flushing turbidity currents carried a globally significant mass of terrestrial organic carbon down just one submarine canyon in a single year, indicating their importance for redistribution and delivery of organic carbon to the deep sea.

## INTRODUCTION

Photosynthesis by plants removes $CO_2$ from the atmosphere and forms organic matter containing organic carbon (OC). A fraction of this terrestrial OC travels via rivers to the coast and is deposited in marine sediments (Blair and Aller, 2012). The burial of OC in marine sediments over geological timescales leads to a net drawdown of atmospheric $CO_2$, aiding regulation of the long-term climate (Berner, 1982; Hilton and West, 2020). It is increasingly recognized that OC can be efficiently transported and buried in the deep sea by turbidity currents travelling down active submarine canyons (e.g., Kao et al., 2014; Sparkes et al., 2015; Talling et al., 2024), with >9,500 canyons worldwide (Harris et al., 2014).

Many previous analyses of global OC burial in marine sediments overlooked the role of turbidity currents and submarine canyons (e.g., Berner, 1982; Burdige, 2005, 2007). Although

many canyons are assumed inactive due to the current sea level high-stand, a number of canyons in a range of settings have remained active (Covault and Graham, 2010; Heijnen et al., 2022a). Studies indicate that the mass of OC transported through canyon-channels and buried in submarine fans (e.g., Bengal Fan, Congo Fan) can be significant (Galy et al., 2007; Rabouille et al., 2019).

Sediment and OC within canyons can undergo multiple cycles of erosion, transport and deposition via relatively small 'canyon-filling' turbidity currents, which runout in the canyon-channel. Occasionally, powerful and long runout 'canyon-flushing' turbidity currents erode and transport material to the depositional lobe (Heijnen et al., 2022b; Pope et al., 2022). Uncertainties in turbidity current recurrence intervals and runout distance are combined with limited measurements of quantity, age, and composition of OC in canyon-channel deposits. This has resulted in a knowledge gap on how turbidity currents move OC within canyons and, crucially, the potential for OC storage within this part of the global sedimentary system.

Here, for the first time, we combine time-lapse seafloor bathymetric maps, sediment cores, and direct flow-monitoring data to understand how OC is transferred and buried in the deep sea by turbidity currents. We present a well-constrained OC budget for the Congo Canyon, offshore West Africa, covering an exceptional one-year period when the canyon experienced two powerful (5-8 m $s^{-1}$) and long (>1,000 km) runout canyon-flushing flows (Talling et al., 2022). Our objectives are: (1) to show how OC is distributed within the Congo Canyon floor facies and derive an OC budget for the canyon; (2) upscale the OC canyon budget to quantify the mass of OC eroded from the Congo Canyon-Channel, and compare this value to global fluxes of terrestrial OC; (3) compare the Congo Canyon, River and Lobe OC signatures to produce a conceptual model for efficient transport of terrestrial OC through river-connected submarine canyons.

## STUDY AREA AND METHODS

The Congo Canyon is directly connected to the Congo River, the second largest river in the world by discharge, and fifth largest for annual particulate OC export (Fig. 1; Babonneau et al., 2002; Coynel et al., 2005). In the deeply incised canyon, turbidity currents have been recorded for ~33% of the time during monitoring periods (Azpiroz-Zabala et al., 2017). At ~2,000 m water depth the canyon transitions to a less incised channel that continues downslope to the lobe at ~5,000 m water depth.

In September-October 2019, seven piston cores were collected from the canyon thalweg between 1577 m and 2173 m water depth. The cores were scanned with a Multi-Sensor Core Logger, split, and visually logged, with five sedimentary facies identified (Fig. 2). Individual beds could not be correlated between cores due to highly variable deposits. Seventy samples from different facies were analyzed for grain size. To determine the OC quantity, source (terrestrial or marine), and age, the same samples were analyzed for total organic carbon (TOC) content, carbon stable isotope composition ($\delta^{13}C$) and radiocarbon content (expressed as 'fraction modern', Fm, a measurement of the deviation of the $^{14}C/^{12}C$ ratio of a sample from "modern"; Supplemental Methods).

To record turbidity currents between October 2019 to May 2020, 11 acoustic Doppler current profiler (ADCP) moorings and 12 Ocean Bottom Seismographs (OBSs) were deployed along the Congo Canyon-Channel (Fig. 1; Talling et al., 2022; Supplemental Methods). A powerful turbidity current broke the moorings and two seafloor telecommunications cables on 14-16$^{th}$ January 2020, with the repaired cables broken again by a major flow on 8$^{th}$ March 2020.

To calculate the Congo Canyon OC budget, the net eroded sediment volume from the canyon floor was determined using the September-October 2019 and October 2020 multibeam

surveys, collected with a Kongsberg EM122 echosounder (Fig. 1). The net eroded sediment volume was divided into the facies proportions averaged across the sediment cores and converted to sediment mass, using the average facies porosity ± 1 standard deviation to get sediment density (Table S1, S2). The OC mass eroded was calculated using the average TOC ± 1 standard deviation for each facies (Table S3). An OC budget for the full Congo Canyon-Channel was estimated using a facies porosity range and the TOC of Congo Channel sediments from Baudin et al. (2020), and a total eroded sediment volume of 2.68 $km^3$ (Talling et al., 2022; Supplemental Methods).

## RESULTS

### Sedimentary facies and organic carbon composition

The Congo Canyon thalweg cores contain five facies, which are now described along with their OC composition (Figs. 2 and 3; Table S3, S4): (1) **Clay** is homogenous or bioturbated and comprises 47% of the cores. The facies has a high TOC (reported as the mean, $TOC_{av,}$ ± 1 standard deviation) of 3.51 ± 0.60% and an OC age (reported as the mean Fm, $Fm_{av}$ ± 1 standard deviation) of 0.94 ± 0.04. (2) **Silt** (18% of the cores) contains occasional laminations or normal grading to clay and may be homogeneous or bioturbated. This facies has OC $Fm_{av}$ = 0.95 ± 0.02 and $TOC_{av}$ = 2.60 ± 0.99%. (3) **Muddy sand** (22% of the cores) comprises mud with fine- to medium-grained sand, that may be ungraded or normally graded, and can contain clasts. This has a lower $TOC_{av}$ = 1.81 ± 1.74%, and older OC ($Fm_{av}$ = 0.91 ± 0.06) compared to clay or silt. (4) **Sand** comprises clean, fine- to medium-grained sand with rare clasts and is often ungraded or occasionally normally graded. Sand facies comprises 9% of the cores, with low $TOC_{av}$ = 0.49 ± 0.26% and the oldest OC with $Fm_{av}$ = 0.78 ± 0.06. (5) **Vegetation-rich muddy sand** contains concentrated, well-preserved mm- to cm-sized black wood and plant debris (Fig. 2C) within a fine-grained sand-mud matrix with no grading. This facies only makes up 4% of the cores but contains high $TOC_{av}$ = 8.24 ±

2.24%, and the youngest OC, $Fm_{av}$ = 0.99 ± 0.02. Most of the facies $\delta^{13}C$ values are depleted (−28.5‰ to −26‰), indicating a terrestrial origin for the OC, consistent with Congo River sediment samples (Fig. 3B; Hemingway et al., 2017).

**Turbidity currents in the canyon**

The ADCP-moorings, cable breaks and OBS stations recorded 19 turbidity currents in the Congo Canyon-Channel over 8 months. The majority (17) of the flows terminated in the canyon (runout distance <190 km; 2 flows), or before reaching the deep-water channel (runout distance <791 km; 15 flows), with an average 3.7 m $s^{-1}$ transit velocity (Fig. S1). However, two turbidity currents travelled >1,000 km and reached transit velocities of 5.7 and 7.6 m $s^{-1}$. These large, cable-breaking, flows were preconditioned by major river floods (with return intervals of 20-50 years), but occurred weeks to months after the flood peak, often during spring tides (Talling et al., 2022).

**Sediment and organic carbon budget**

The bathymetric difference map shows significant erosion occurred along the canyon thalweg over one year (Fig. 1C, D). The net eroded sediment volume along the 112 km-surveyed length of canyon is 0.32 $km^3$. This equates to 226 ± 36 Mt of sediment and 6.09 ± 2.70 Mt of terrestrial OC eroded over one year. The clay facies contributed the largest amount of eroded OC (3.13 ± 0.87 Mt), followed by silt (1.24 ± 0.60 Mt), muddy sand (0.91 ± 0.88 Mt), vegetation-rich muddy sand (0.66 ± 0.25 Mt) and sand (0.15 ± 0.09 Mt; Fig. 3D).

## DISCUSSION

**How is organic carbon distributed within the Congo Canyon thalweg?**

The Congo Canyon thalweg contains varied sedimentary deposits, with a strong link between facies type and TOC. The $\delta^{13}C$ values indicate that the OC has a terrestrial source. Overall,

6.09 ± 2.70 Mt of OC was eroded in the Congo Canyon over one year (Fig. 3). The cores are dominated by high TOC, fine-grained facies (69% clay and silt) which held 72% of the canyon OC budget (Fig 3C, D), showing that the canyon of this mud-rich system is primarily fine-grained. Clay and silt are associated with high TOC values as minerals in these sediments form chemical bonds with OC, preventing oxidation (Hemingway et al., 2019). The age of the clay and silt OC ($Fm_{av}$ of 0.94 ± 0.04 and 0.95 ± 0.02) likely corresponds to a mixture of young terrestrial biospheric OC and old terrestrial biospheric OC from degraded organic matter in the Congo Basin, as indicated by Congo River OC Fm of 0.89 ± 0.07 (Hemingway et al., 2017).

The Congo Canyon cores contain only a modest amount of sand (9%) and muddy sand (18%). These sand-rich facies contained low TOC, and thus provided only 17% of the OC in the budget (Fig 3D). The sand facies contained the oldest OC in the canyon ($Fm_{av}$ = 0.78 ± 0.06). This suggests large contributions to the bulk Fm measurements from old terrestrial biospheric OC or petrogenic OC ($^{14}$C-free OC from eroded rocks), as seen in coarse-grained deposits in other turbidite systems (e.g., Hage et al., 2020).

The vegetation-rich muddy sand facies made up only 4% of the total facies yet contributed 11% of the canyon OC budget due to a high $TOC_{av}$ of 8.24 ± 2.24% (Fig. 3). Prior work in turbidite systems also concluded that sandy facies can contribute to OC burial in marine sediments due to plant debris (Lee et al., 2019; Hage et al., 2020). However, these studies observed plant debris in cleaner-sand turbidite units (i.e., $T_B$ and $T_D$ of the Bouma sequence), rather than the muddy-sand matrix that contained plant debris in the Congo Canyon. This suggests different hydrodynamic sorting of plant debris by mud-rich turbidity currents compared to sandy flows. The vegetation-rich muddy sand had a $Fm_{av}$ = 0.99 ± 0.02, indicating the dominance of young terrestrial biospheric OC derived recently from the atmosphere (within the last ~100 years). Burial of this fresh material

in marine sediments represents a relatively rapid removal of $CO_2$ from the atmosphere (Lee et al., 2019).

**Comparison of organic carbon eroded along the Congo Canyon-Channel to global fluxes**

The >1,000 km runout flows eroded 2.68 $km^3$ of seabed sediment along the Congo Canyon-Channel (Talling et al., 2022). Facies and TOC trends down the Congo Channel are poorly constrained. Cores suggest there is a transition from the diverse, TOC-rich canyon sediments to sandy channel sediments with an estimated TOC of 2.0 ± 0.1%. (Baudin et al., 2010, 2017, 2020). Using this TOC value for the remaining 2.36 $km^3$ of eroded sediment, we estimate that 43 ± 15 Mt of terrestrial OC was eroded along the Congo Canyon-Channel in one year by two canyon-flushing turbidity currents (Supplemental Methods). This is a globally-significant mass of eroded OC, equivalent to 22% of annual global particulate OC export from all rivers to the oceans (200 Mt/year; Galy et al., 2015) and 54-108% of the annual terrestrial OC predicted to be buried in the global ocean (40-80 Mt/yr; Hilton and West, 2020). While the return interval of canyon-flushing flows and the annual rate of OC transfer by turbidity currents cannot yet be assessed, this study shows that the mass of terrestrial OC transferred to the deep sea by turbidity currents can contribute to global OC fluxes.

**Efficient transport of terrestrial organic carbon through river-connected submarine canyons**

Direct monitoring recorded multiple low-velocity 'canyon-filling' turbidity currents terminating in the Congo Canyon-Channel. Two faster, >1,000 km runout, strongly erosive 'canyon-flushing' events were also recorded (Fig. S1). This is consistent with magnitude-frequency-runout studies of shallow-water turbidity currents (Heerema et al., 2020; Heijnen et al., 2022b). These flow observations are combined with OC signature data in the Congo River, Canyon, and Lobe to inform our OC transport model (Fig. 4).

The canyon-filling flows rapidly bury sediment and OC in the upper canyon-channel, helping to protect OC from degradation, and producing high TOC deposits (Fig. 4B; Hedges and Keil, 1995). Frequent canyon-filling flows may erode and rework the sediment and OC, exposing the OC to oxygenating conditions. However, despite such reworking, the age and origin of terrestrial OC in the Congo Canyon (Fm = 0.92 ± 0.08; $\delta^{13}C$ = -26.91 ± 0.84) is similar to that of terrestrial OC in the Congo River (Fm = 0.89 ± 0.07; $\delta^{13}C$ = -26.44 ± 0.77; Hemingway et al., 2017). This suggests highly efficient OC transport through this part of the system on contemporary timescales.

The OC deposited in the upper canyon-channel is temporarily stored for ~10s of years, before canyon-flushing flows, triggered by river floods with recurrence intervals of 20-50 years (Talling et al., 2022), erode the material and quickly transport it to the deep sea, along with relatively fresh OC from the Congo River floods (Fig. 4C). Flushed material is rapidly deposited on the lobe, protecting OC from degradation, and sequestering OC for long timescales (Galy et al., 2007). The Congo Lobe OC age has been measured as Fm = 0.89 and Fm = 0.80 (Savoye et al., 2009), which is similar to Congo Canyon and River Fm-values, supporting this model for efficient OC transport from river-mouth to lobe. Thus, canyon-flushing turbidity currents can efficiently transport globally significant amounts of terrestrial OC to the deep sea, indicating their importance for organic carbon budgets.

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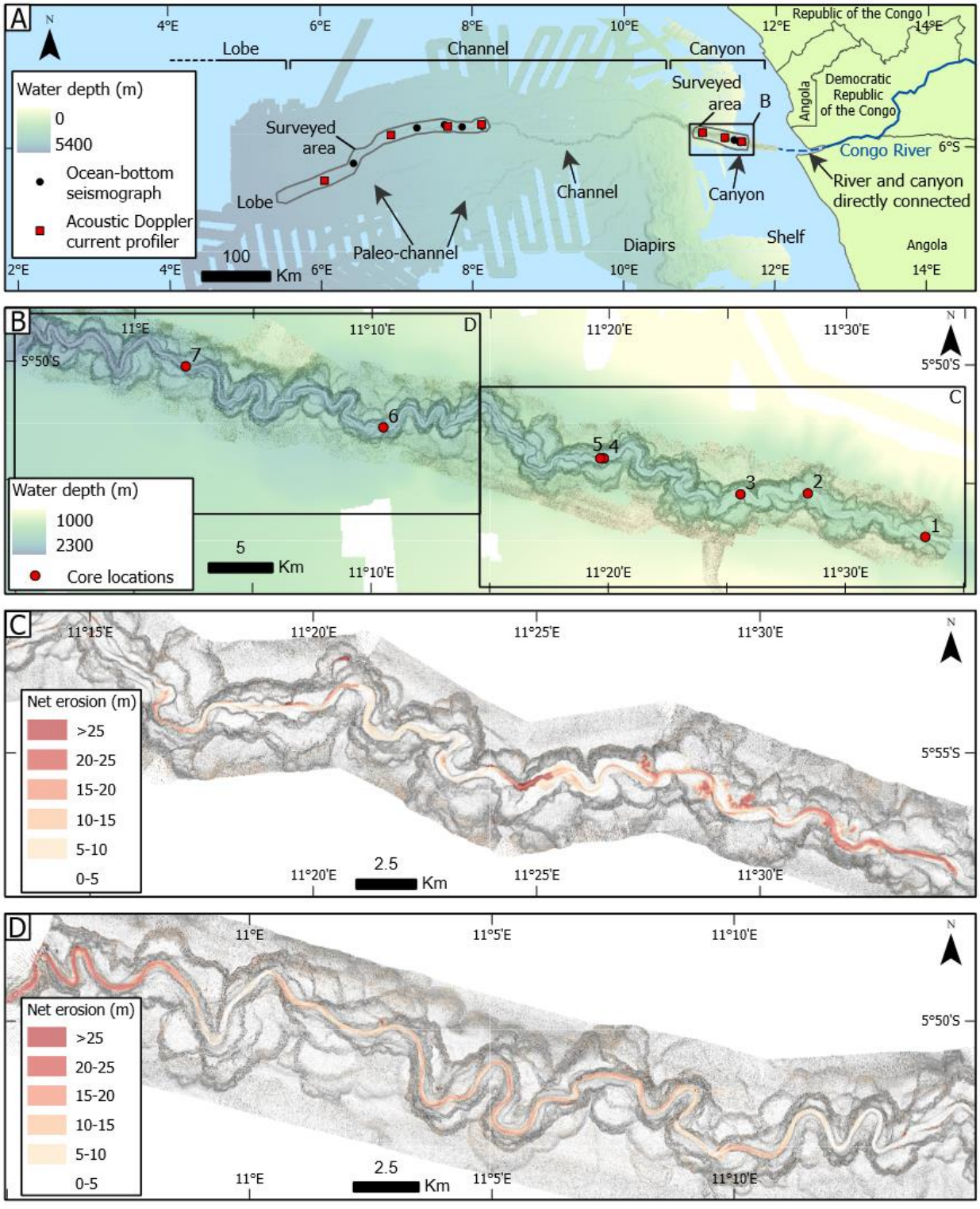
## FIGURE CAPTIONS

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304 Figure 1. Study site. A) Bathymetric map of the Congo Submarine Fan (offshore West Africa)

305 and instruments deployed to record turbidity currents. B) 2019 Congo Canyon bathymetry and

sediment core sites. C) and D) October 2019 – October 2020 elevation difference map showing canyon thalweg net erosion.

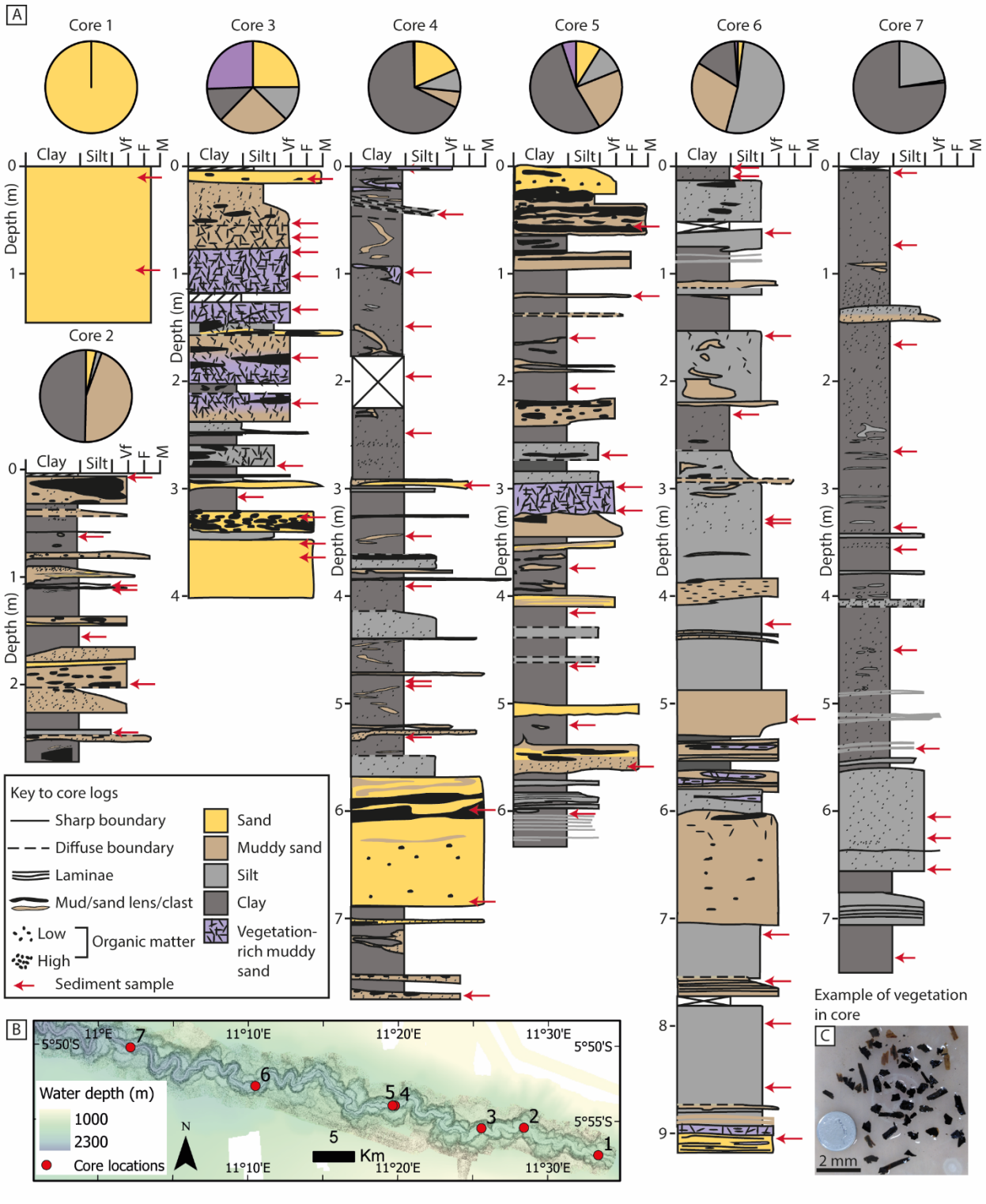

Figure 2. Congo Canyon thalweg cores collected October 2019. A) Core logs show the diverse range of facies eroded by 2020 canyon-flushing turbidity currents. B) Map of core locations. C) Photo of mm-size plant debris in the cores.

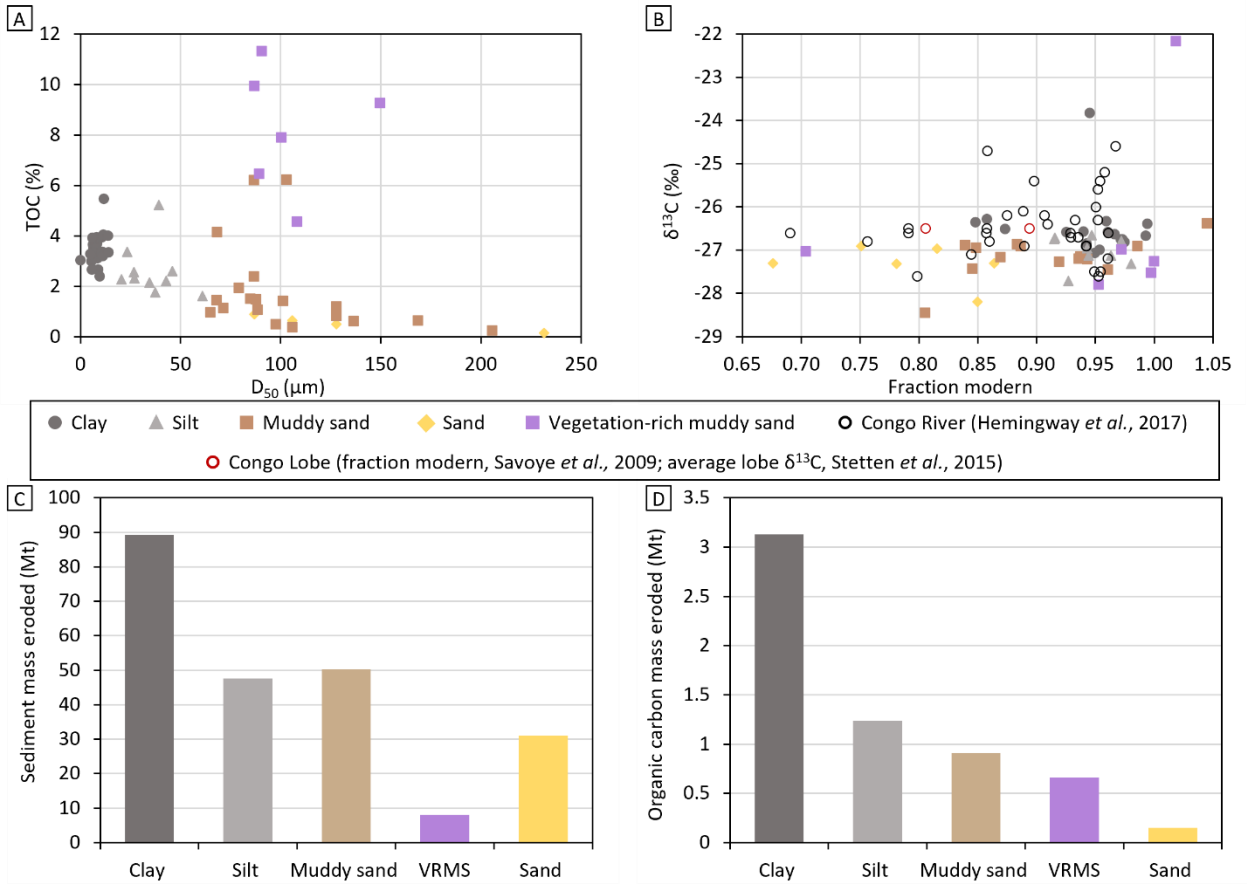


Figure 3. Congo Canyon organic carbon data and budget by facies. A) Total organic carbon (TOC) content against median grain size (D50). B) Carbon stable isotope ratios ($\delta^{13}C$) versus radiocarbon age (fraction modern), with published data from Congo River and Lobe. C) Sediment and D) organic carbon mass eroded from the canyon in one year.

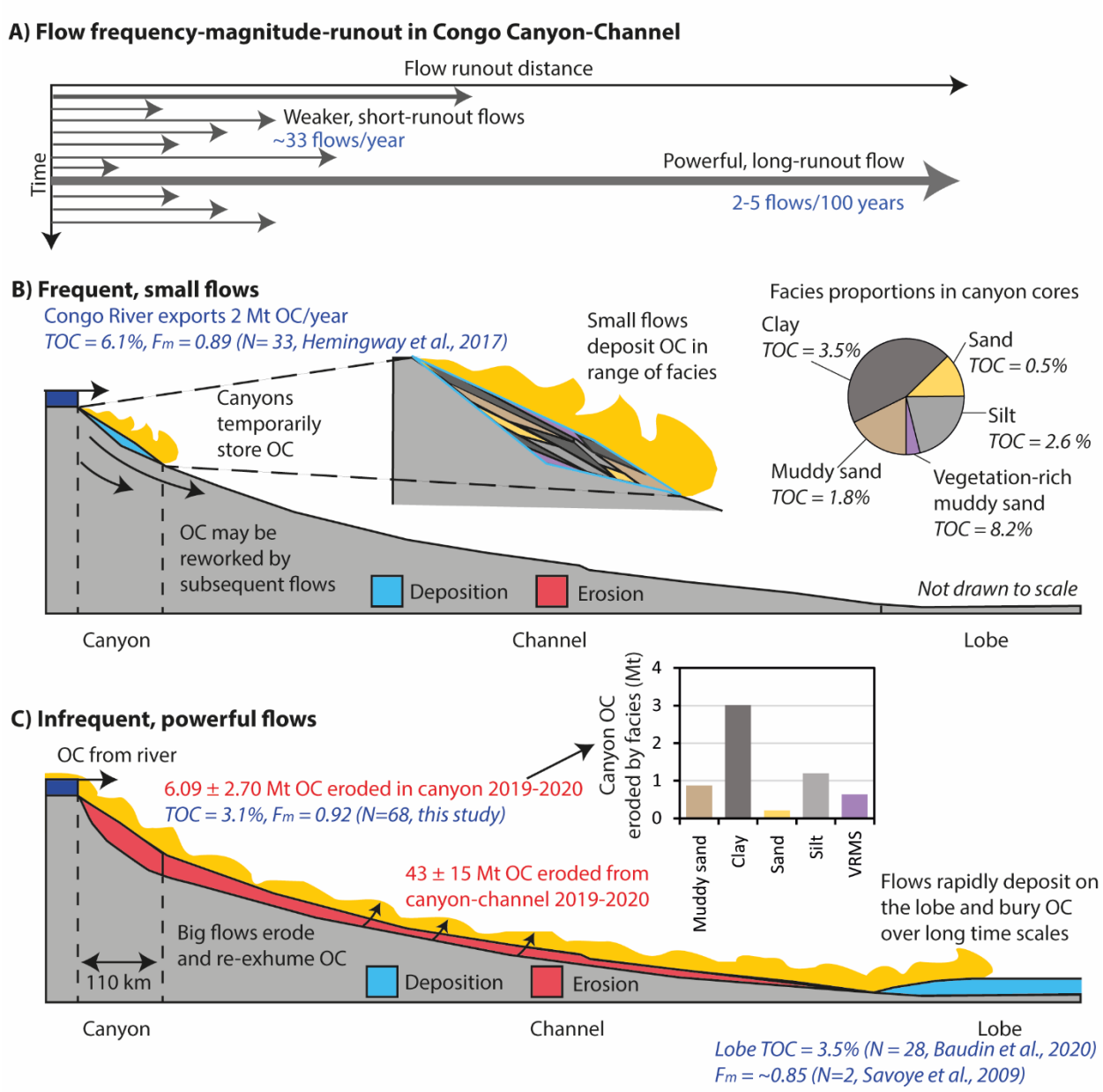


Figure 4. Efficient transport of terrestrial organic carbon (OC) through active submarine canyons connected to rivers. A) Congo Canyon-Channel turbidity currents are mainly 'canyon-filling' flows with occasional 'canyon-flushing' flows. B) Canyon-filling flows deposit sediment and organic carbon in a range of facies. C) Canyon-flushing flows erode and transport sediment and organic carbon to the lobe for long-term burial. VRMS = vegetation-rich muddy sand.

[1]Supplemental Material. Supplemental Methods (Deployment and specification of monitoring equipment, turbidity current identification, time-lapse seafloor surveys and analysis of sediment samples). Tables S1–S5 and Figure S1. Please visit https://doi.org/10.1130/XXXX to access the supplemental material, and contact editing@geosociety.org with any questions.