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Terrestrial organic carbon processing and dispersal on a high-energy, river-dominated margin

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Key Points:

- Burial of terrestrial organic carbon offshore of the Ayeyarwady Delta is higher than previously estimated, despite high-energy oceanographic conditions on the continental shelf.
- Terrestrial organic carbon accumulating in the offshore delta is refractory and remains largely unmodified during shelf transport.
- Initial remineralization of terrestrial organic carbon is likely limited to the near-shore environment, instead of mobile mud shelf deposits as previously postulated.

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

Abstract

The Ayeyarwady and Thanlwin Rivers deliver ~1.9 Mt y^{-1} of particulate terrestrial organic carbon (TerrOC) to the Northern Andaman Sea making them one of the largest sources of TerrOC to the world ocean. Offshore, fluvial material is extensively mixed by tides and estuarine circulation in the Gulf of Martaban, concurrently incorporating marine organic carbon. While previous bulk stable isotope analyses have suggested that frequent resuspension enhances TerrOC degradation, limiting burial on high-energy margins, in this study we use ramped pyrolysis/oxidation (RPO) and radiocarbon analysis to identify high and uniform TerrOC content (by Wt. %) in continental shelf sediments offshore of the Ayeyarwady Delta. By analyzing sediment samples from the river mouths and across the shelf, RPO results demonstrate consistent radiocarbon and stable carbon isotope composition ($\delta^{13}C$) of TerrOC from the Gulf of Martaban to the mid-shelf clinoform depocenter, suggesting that extensive degradation does not occur during shelf transport. Instead, rapid remineralization and processing of labile material likely occurs near-shore, while refractory terrestrial components are efficiently transported to the mid-shelf depocenter. Given $\delta^{13}C$ values of refractory TerrOC fractions that mimic marine sources, we suggest that offshore TerrOC content has been substantially underestimated by bulk $\delta^{13}C$-based mixing models. Providing a new conceptual framework for organic carbon preservation in this globally significant offshore delta, these findings indicate the necessity of re-evaluating our understanding of TerrOC processing on high-energy, river-dominated margins, and support recent hypotheses that these systems provide a larger sink for TerrOC than previously suggested.

Keywords: Terrestrial Organic Carbon, Organic Carbon Burial, Remineralization, Continental Shelf, Ayeyarwady Delta, High-Energy Margin

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

1. Introduction

Rivers exert a dominant control over the transport of particulate terrestrial organic carbon (hereafter TerrOC) with global delivery of ~200 Mt C y^{-1} to the world ocean (Galy et al., 2015). As such, river-dominated margins are major repositories for TerrOC, especially along margins where rapid burial can effectively preserve TerrOC over geologic timescales (Galy et al., 2007; Leithold et al., 2016). However, the fate of TerrOC in the marine environment is suggested to be controlled by the contrasting roles of oxidation through frequent resuspension and rapid burial (Blair & Aller, 2012; Leithold et al., 2016; Bianchi et al., 2018), with a currently estimated ~55-80% of the global organic matter flux being remineralized (Burdige et al., 2005; Blair & Aller, 2012). Because some of the world's largest rivers discharge onto high-energy margins with strong tidal currents (e.g. the Amazon, Yangtze, and Ganges-Brahmaputra Rivers), the contrasting potential for oxidation and rapid burial convolutes our understanding of the fate of TerrOC in these dynamic systems. In this case, the character of the TerrOC (i.e., reactivity, composition, and mineral protection) delivered to margins determines the response to energetic oceanographic processes and the ultimate propensity for remineralization and / or resistance to degradation and burial (Blair & Aller, 2012; Bianchi et al., 2018; Hemingway et al., 2019). Therefore, a thorough understanding of the processes shaping TerrOC cycling at high-energy, river-dominated margins is crucial for interpreting its subsequent fate in the marine environment.

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

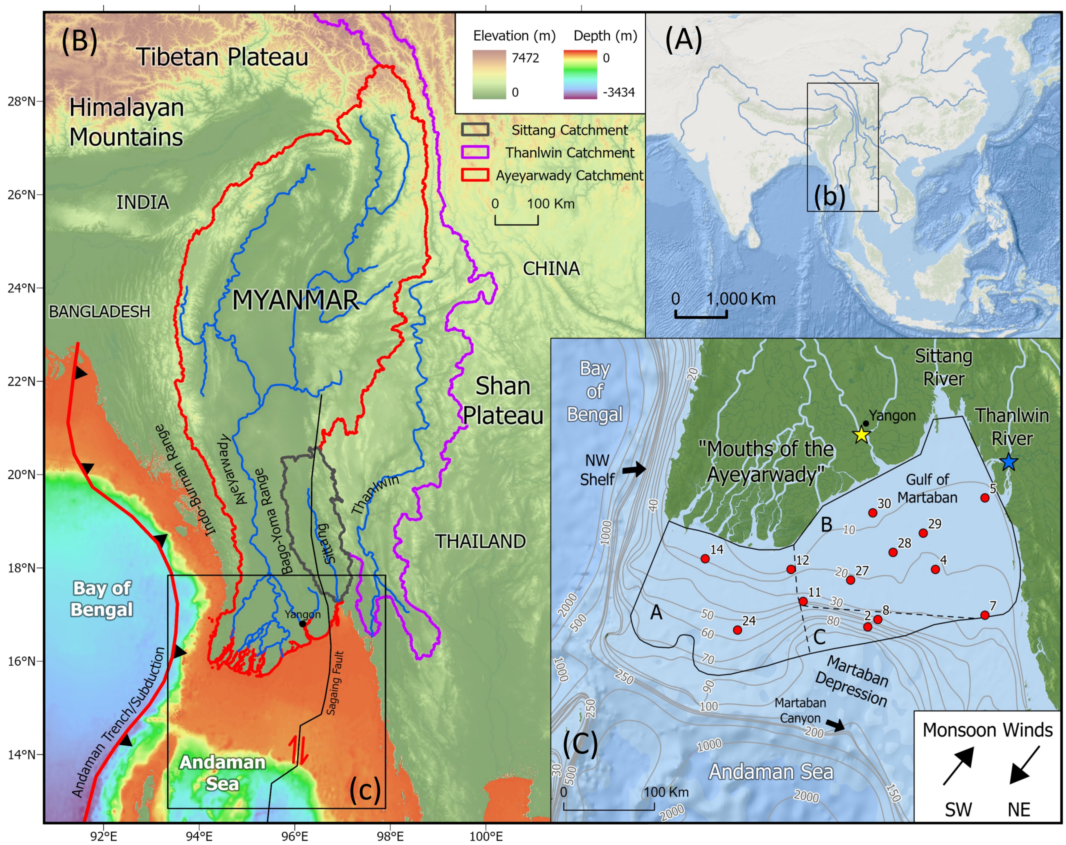

Figure 1. Location map for the Ayeyarwady Delta region indicating (A) the Ayeyarwady and Thanlwin Rivers with respect to other regionally significant rivers in Asia, (B) the Ayeyarwady, Thanlwin, and Sittang River catchments and the tectonic setting of the region (Bathymetry from The GEBCO Digital Atlas published by the British Oceanographic Data Centre on behalf of IOC and IHO, 2003), and (C) a map of the offshore study area with coring locations indicated by red circles and river end-member samples denoted by stars with the Ayeyarwady in yellow and the Thanlwin in blue (Kuehl et al., 2019). The area of modern offshore accumulation is indicated by the black polygon as defined by Flynn et al. (2022). Various offshore depositional regions are separated by dashed lines and include (A) the "Mouths of the Ayeyarwady," (B) the Gulf of Martaban, and (C) the Martaban Depression. Smoothed bathymetric contours (gray lines) are shown in meters water depth (adapted from The GEBCO Digital Atlas published by the British Oceanographic Data Centre on behalf of IOC and IHO, 2003).

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

Rivers in Asia account for a substantial portion of the global sediment (ca. 70%) and TerrOC (ca. 60%) flux to the ocean (Liu et al. 2009; Milliman & Farnsworth, 2011; Luo et al., 2022). Of these rivers, the Ayeyarwady and Thanlwin (A-T) Rivers in Myanmar deliver ~485 Mt of sediment and ~1.9 Mt of TerrOC to the Northern Andaman Sea annually, making this combined river system one of the largest point sources of TerrOC to the global ocean (Figure 1) (Baronas et al., 2020). Notably, unlike many Asian rivers, the A-T river mainstems remain undammed, keeping the large sediment and TerrOC loads of the rivers relatively unaltered over modern timescales (Milliman & Farnsworth, 2011; Grill et al., 2019). Discharging into the Northern Andaman Sea, the A-T rivers feed the offshore Ayeyarwady Delta (Figure 1). A monsoonal climate and a macrotidal environment drive energetic conditions on the shelf that facilitate the formation of diagenetic regimes associated with TerrOC remineralization, such as fluid muds and a deep sediment surface mixed layer (SML) (Aller et al., 1996; Aller, 1998; Aller & Blair, 2006; Bianchi et al., 2018; Kuehl et al., 2019; Flynn et al., 2022; Harris et al., 2022). Despite these energetic conditions, a recent TerrOC mass budget that utilized bulk stable isotopes estimated that offshore burial may approach as much as 100% relative to the most recently estimated fluvial load values (Baronas et al., 2020; Flynn et al., 2022). Nonetheless, previous studies have found that remineralization of TerrOC may still occur on the Northern Andaman Sea continental shelf based on across-shelf changes in bulk stable isotopes (Ramaswamy et al., 2008; Flynn et al., 2022; Flynn & Kuehl, 2025). Because of the inherent limitations of bulk sediment analyses and the utilization of bulk isotope mixing models (e.g., Williams et al., 2015; Boehman, 2025), the contrasting roles of efficient burial and remineralization on the Northern Andaman Sea shelf and the composition of the various TerrOC components accumulating in offshore deposits remain largely unknown. Due to the substantial flux of material from the A-T rivers, determining the balance between remineralization and preservation of TerrOC components of varying reactivities within the offshore delta has important implications for the estimation of regional and global carbon budgets.

While studies using elemental, and stable and radio-isotope analyses have begun to illuminate the source to sink fate of TerrOC, they are limited by the inability to adequately separate various particulate organic carbon (hereafter OC) pools out of the complex mixtures present in margin systems (Rosenheim & Galy, 2012). Such mixtures, which are especially characteristic of deltaic environments with high sediment loads, include an array of OC sources with varying reactivity ranging from labile marine OC to modern and pre-aged terrestrial biospheric components, and more refractory radiocarbon-dead petrogenic material (Galy et al., 2007; Galy et al., 2015; Hemingway et al., 2017b; Bianchi et al., 2018; Zhang et al., 2022). The ramped pyrolysis/oxidation (RPO) method, has emerged as an effective analytical approach to separate OC mixtures based on the thermochemical stability of various components (Rosenheim et al., 2008). Coupled with stable and radio-carbon isotope analysis of CO_2 fractions collected during combustion, the OC composition and age distributions within a sample can be identified. This method has, for instance, been employed to investigate organic carbon aging through selective degradation and transport time offshore of the Yellow and Yangtze Rivers (Bao et al., 2018; Bao et al., 2019), to identify the preservation of pre-aged Loess soils off the Yellow River (Zhang et al., 2022), and to quantify the preservation of terrestrial material in the Amazon mobile mud banks system (Williams et al., 2015; Boehman, 2025).

In this study we utilize RPO and isotope analysis methods to investigate TerrOC content and composition in the offshore Ayeyarwady Delta, with the aim of determining the quantity and nature of TerrOC components dispersed offshore and to what extent remineralization may occur

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

during shelf transport. Through RPO analysis of 13 sediment samples from the offshore delta and two river end-members, we characterize the thermochemical stability and reactivity of OC components using calculations of activation energy from RPO thermograms and the isotopic analysis of CO_2 fractions. Based on RPO isotopic compositions we identify a continuum of fluvial OC components and employ a $\delta^{13}C$ binary mixing model with sample-specific TerrOC end-members to estimate TerrOC content across the offshore delta. The spatial distribution of TerrOC isotopic compositions and TerrOC content are explored to assess potential remineralization associated with sediment transport pathways on the Northern Andaman Sea shelf. We then compare the TerrOC content derived from RPO analyses to that derived from bulk isotope end-members to assess these distinct approaches. Together, this presents a new conceptual framework for the processing of TerrOC on high-energy, rive-dominated margins.

2. Background

2.1. Regional rivers

Rising on the Tibetan Plateau, the A-T rivers together drain the vast majority (83%) of Myanmar, as well as regions of southwest China and eastern Thailand (Figure 1) (Bender, 1983). Of the two rivers, the Ayeyarwady has a larger catchment (413x10^3 km^2) and sediment load reaching ~326 Mt y^{-1}, while the Thanlwin transports ~159 Mt y^{-1} through a smaller (~324x10^3 km^2) catchment (Baraonas et al., 2020). Nonetheless, both rivers transport similar amounts of TerrOC to the ocean, at ~1 Mt y^{-1} each (Baronas et al., 2020). In addition, 50 Mt y^{-1} of sediment and an unknown quantity of TerrOC is delivered to the Northern Andaman Sea by smaller regional rivers, including the Sittang River located between the A-T river catchments (Figure 1) (Robinson et al., 2007).

The A-T river catchments are characterized by predominately sub-tropical climate zones with distinct wet and dry seasons driven by the Indian Monsoon. Myanmar's central valley and lowlands fall in the rain shadow of the Indo-Burman Range (IBR), producing relatively dry savanna throughout the mid and lower reaches of the Ayeyarwady catchment with forest cover limited to mountainous regions (Blasco et al., 1996). Despite strong climatic seasonality, TerrOC composition in the Ayeyarwady River exhibits only slight seasonal variation in $\delta^{13}C$ during times of low and high flow. For instance, low flow periods are associated with $\delta^{13}C$ ranging from -25.4‰ to -25.9‰ due to increased forest or alpine derived carbon (C_3 pathway) input, which nearly overlaps with the -24.0‰ to -25.2‰ range produced by monsoon-driven high flows that include the minor input of savanna-derived carbon (C_4 pathway) during seasonal flooding (Bird et al., 2008). Conversely, majority of forest cover in the Thanlwin catchment is in the lower reaches, while alpine grassland is prominent at the headwaters (Bird et al., 2008). With no floodplain and no significant proportion of C_4 vegetation, the $\delta^{13}C$ of TerrOC within the Thanlwin is consistently below -25‰ (Bird et al., 2008). During the dry season TerrOC content is similar in the two rivers; however, during the wet season TerrOC content is higher in the Thanlwin (Bird et al., 2008).

Modern human development has begun to alter the composition of sediment fluxes in the Ayeyarwady River as evident through geomorphologic changes along the shoreline of the delta plain (Webb et al., 2014; Anthony et al., 2019; Chen et al., 2020; De Alban et al., 2020; Vogel et al., 2022). For example, mangrove deforestation has led to an increase in fine sediment fluxes and contributed to localized coastal accretion, whereas mainstem sediment mining has reduced coarse sediment loads, driving localized coastal erosion (Anthony et al., 2019). While similar development has occurred in the Thanlwin, variations in fluxes have yet to be investigated.

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

Nonetheless, unlike many large Asian rivers, the A-T rivers remain relatively unimpeded, with damming currently limited to river tributaries (Grill et al., 2019). However, future plans to install large hydropower dams on both river mainstems suggest that river connectivity and particle fluxes may be substantially altered in coming years (Hennig et al., 2016; Johnston et al., 2017).

2.2. Subaerial and subaqueous delta formation

The Ayeyarwady River meets the head of its large delta plain ~270 km north of the modern shoreline. Progradation of the delta plain occurred over the mid- to late Holocene until ~1 ka, at which point the subaerial delta front reached the southern-most extent of the subaerial IBR where increased focusing of wave energy on the emerging headland limited further subaerial growth (Giosan et al., 2018). For the last ~150 years high energy oceanographic conditions have effectively kept the subaerial delta front in a state of relative equilibrium (Hedley et al., 2009), with the majority the Ayeyarwady's sediment load being exported to, and retained on, the Northern Andaman Sea shelf (Flynn et al., 2022).

Monsoon winds drive seasonally reversing surface currents on the shelf. During May through September, the SW monsoon drives easterly surface currents and brings majority of the region's annual rainfall (90%), while during December through February the drier NE monsoon drives westward surface currents (Rodolfo, 1969). Sediment transport models suggest that despite seasonal surface current reversal, a majority of the sediment discharged from the Ayeyarwady distributaries may be transported east to the Gulf of Martaban by near-bed currents (Fair, 2021). During the SW monsoon, wave heights can reach up to 2 m, and as high as 5 m during intermonsoonal cyclonic events (Besset et al., 2017). The offshore region is characterized as macrotidal, with semidiurnal tides with M2 (principal lunar) and S2 (principal solar) major components (Ramaswamy et al., 2004). In the Gulf of Martaban, a local tidal range of 4 – 7 m

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

and tidal currents up to 3 m s^{-1} creates a vast zone of perennial turbidity that can span >45,000 km^2 with spring tides (Ramaswamy et al., 2004). Strong tidal currents in the shallow (<30 m) Gulf of Martaban drive the formation of fluid muds, a deep (up to 1 m) SML, and limited accumulation (Kuehl et al., 2019; Flynn at al., 2022; Harris et al., 2022). Sediment transport from the Gulf of Martaban to the subaqueous delta in the Martaban Depression is anticipated to occur via tidal currents and / or event driven gravity flows (Kuehl et al., 2019; Liu et al., 2020; Harris et al., 2022; Flynn et al., 2025). Exhibiting accumulation rates as high as ~6 cm y^{-1} in foreset beds, the Martaban Depression is the primary depocenter for terrestrial material on the shelf (Kuehl et al., 2019; Flynn et al., 2022). Marine OC content increases from the Gulf of Martaban to the Martaban Depression as tidal energy and turbidity decrease, giving way to increased light availability (Ramaswamy et al., 2008; Ramaswamy & Rao, 2014). At the present-day highstand, it appears that no off-shelf sediment export occurs from the Martaban Depression to the deep sea (Kuehl at., 2019; Liu et al., 2020).

On the western side of the Northern Andaman Sea shelf, the "Mouths of the Ayeyarwady" region exhibits relatively low accumulation rates. Primarily consisting of a patchy mixture of modern and relict sands and muds (Ramaswamy et al., 2008). In the western region, much of the fine sediment is winnowed through frequent resuspension by large swell from the Bay of Bengal (Kuehl et al., 2019; Fair, 2021; Flynn et al., 2022). The highest accumulation rates off the "Mouths of the Ayeyarwady" occur in a narrow, nearshore mud belt (<40 m water depth) due to proximal deposition at the distributary mouths (Kuehl et al., 2019).

3. Methods

3.1 Sample collection

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

In this study we capitalize on samples previously collected by Kuehl et al. (2019) in December 2017 as a part of an inter-disciplinary research cruise to the offshore Ayeyarwady Delta (Figure 1). This includes 13 surface (0-2 cm) and / or near-surface (4-14 cm) samples from Kasten cores and two river grab samples from the mouth of the Thanlwin River and near the mouth of the Ayeyarwady's Yangon distributary (in total, N = 15). Details of field sampling are reported in Kuehl et al. (2019).

3.2 Surface area analysis

A Micrometrics Gemini V Surface Area and Pore Size Analyzer was utilized to determine surface area for all offshore samples (N = 13). In preparation, ~1 g of freeze-dried sediment was combusted at 350°C for 12 h for organic matter removal (Yu et al., 2019). Using a Micrometrics FlowPrep 060, samples were then degassed for 0.5 h at 200°C to remove water, before being measured by the five-point Brunauer, Emmett, and Teller (BET) method (Fagerlund et al., 1973). A kaolinite standard was run each day the instrument was operated to ensure instrument accuracy. BET error for all samples was low at an average of ± 0.064 m^2 g^{-1}.

3.3 Bulk isotope analysis

Sediment samples were oven-dried and acidified for bulk stable isotopes analysis. Acidification was conducted at the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility at Woods Hole Oceanographic Institution (WHOI) through acid fumigation methods described by Bao et al. (2018) and Bao et al. (2019). Dried sediment was weighed into a combusted petri dish and placed onto a ceramic tray in a glass vacuum desiccator containing a beaker of 37% HCl. Once sealed, air was evacuated through a stopcock / collar valve and then passively held under vacuum for 72 h at 60°C to remove carbonates. The HCl was then removed and replaced with a beaker of NaOH pellets, and the desiccator was again held under vacuum for

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

24 h at 60°C to neutralize any excess acid. For bulk stable isotope analysis, acidified samples were weighed into double-layered Sn-Ag capsules (~75 mg), pelletized, and sent to the UC Davis Stable Isotope Facility (SIF). Four samples (~20% of N = 19) were prepared to be run in duplicate to determine reproducibility.

At SIF samples were run on an Elementar Vario EL Cube Elemental Analyzer interfaced to an Elementar VisION IRMS to identify Total Organic Carbon (TOC) and carbon stable isotopes ($\delta^{13}C$). All samples were measured relative to the VPDB international standard for $\delta^{13}C$, and precision was ±0.08‰ based on replicate analysis of internal standards. Reproducibility was high with standard deviation between replicates ranging from ±0.10-0.26‰ for $\delta^{13}C$ and ±1.13-4.23 µg for TOC.

3.4 Ramped pyrolysis/oxidation and isotope analysis

RPO was performed at the NOSAMS facility at WHOI and has been described in detail by Rosenheim et al. (2008), Hemingway et al. (2017b), Bao et al. (2018), Hemingway et al. (2018), and others. In summary, acidified (i.e., acid fumigated) sediment was weighed (~200 mg, N = 19) and loaded into a quartz reactor which was then placed into an oven and heated on a linear temperature ramp of 5°C min^{-1} from room temperature to 1000°C. During heating, evolved components were simultaneously oxidized to CO_2 through a stream of ~8% O_2 in He. Using a flow-through infrared CO_2 analyzer, a profile of the thermal evolution (or thermogram) of CO_2 was produced. Evolved CO_2 was cryogenically collected over five temperature windows, which were determined based on the simultaneous evolution of convex and concave features in each thermogram. For all samples, the collection of the first CO_2 thermal fraction began at 60-120°C when measured CO_2 (ppm) began to increase from baseline, and collection ceased for the last fraction at 900-950°C when CO_2 (ppm) returned to near baseline and remained relatively

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

constant. CO_2 aliquots were cryogenically purified and trapped into precombusted glass tubes containing ~50 mg CuO and ~10 mg Ag granules, before being combusted again as a final purification step.

CO_2 fractions (N = 75) were split and analyzed for both stable and radio-carbon isotopes at the Oregon State Stable Isotope Collaboratory and the NOSAMS facility at WHOI, respectively. Stable isotope analysis was conducted using Thermo 253 Plus IRMS Dual Inlet Analysis and µvolume Analysis, calibrated using In-House Wiley, NBS19, and NBS18 $CaCO_3$ standards. Average sample standard deviation of $\delta^{13}C$ microvolume analysis was $\pm$0.013‰. For radiocarbon analysis all gas samples were graphitized through reaction with a Fe catalyst and measured by accelerator mass spectrometry along with a primary standard, NBS Oxalic Acid I (NIST-SRM-4990), secondary standards, and process blanks. Radiocarbon results were reported using the fraction modern (Fm) notation, which indicates the deviation of a sample radiocarbon content from the modern oxalic acid standard (Olsson, 1970) and were corrected for stable isotope fractionation. RPO blank corrections for sample masses, Fm, and $\delta^{13}C$ were made following Hanke et al. (2023) and Hemingway et al. (2017a), and $\delta^{13}C$ was further corrected for kinetic fractionation as described by Hemingway et al. (2017a).

4. Results

4.1 Bulk characteristics

Bulk samples were independently analyzed for TOC, SA, and $\delta^{13}C$, while a mass balance of Fm from RPO fractions was used to derive bulk Fm values (Hemingway et al., 2017a) (Table S1). Bulk TOC ranges from 0.24% to 0.56% with the highest offshore TOC being KC-05 near the mouth of the Thanlwin River and the lowest being KC-12 off the “Mouths of the Ayeyarwady.” Overall, apart from the locations proximal to river mouths, TOC increases north

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

to south from the Gulf of Martaban to the Martaban Depression (Figure 2). SA exhibits a minimal range of 20.6 to 26.8 $m^2 g^{-1}$, with the exception of KC-12 and KC-14, off the "Mouths of the Ayeyarwady" (10.3 and 17.4 $m^2 g^{-1}$, respectively). Bulk $\delta^{13}C$ has a range of -24.5‰ to -21.7‰ and demonstrates an increase in ^{13}C enrichment offshore (Figure 2). Bulk Fm varies from 0.68 to 0.83, with a slight increase from the mid shelf in the Gulf of Martaban to the Martaban Depression and from east to west, similar to bulk TOC (Figure 2). The oldest sample (KC-12) is near the "Mouths of the Ayeyarwady", while the youngest sample (KC-05) is near the mouth of the Thanlwin River (Figure 2).

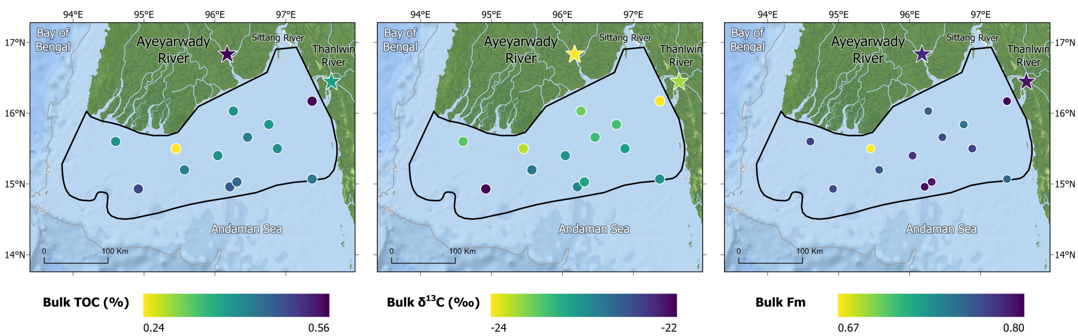

Figure 2. Offshore distribution of total organic carbon (TOC), **δ**^{13}C, and Fm for bulk sediment samples. Region of modern accumulation is indicated by the black polygon, while coring locations are indicated by color-coded circles (Flynn et al., 2022). Locations of Ayeyarwady and Thanlwin River samples are indicated by color-coded stars.

Only bulk TOC and $\delta^{13}C$ were determined for river samples, as no wet or freeze-dried material was available for SA analysis. TOC is higher in the Ayeyarwady at 0.60%, compared to 0.40% in the Thanlwin. Bulk $\delta^{13}C$ is also slightly lower in the Ayeyarwady than in the Thanlwin, being -25.3‰ and -24.8‰, respectively. These values are within the range of those previously reported by Bird et al. (2008) for both rivers (see Section 2.1). Our bulk N/OC values for both rivers (0.11 in the Ayeyarwady and 0.10 in the Thanlwin) also show agreement with those

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

previously reported (i.e., 0.12 in the Ayeyarwady and 0.09 in the Thanlwin; Bird et al., 2008). The minimal discrepancies between previous findings and those presented here may be due to varying locations of river sampling or seasonal variations. The Bird et al. (2008) samples were collected above tidal influence, while our river samples were collected near river mouths and thus may be impacted by additional sources and processing of OC. The bulk Fm values of both rivers are similar (0.79 $\pm$ 0.0009 in the Ayeyarwady, 0.80 $\pm$ 0.010 in the Thanlwin), and indicate a younger age compared to most of the samples from the Gulf of Martaban.

4.2 RPO thermograms and thermal fractions

RPO thermograms are a product of the amount and composition of OC contained within a sediment sample. Overall, all RPO thermograms demonstrate a bimodal distribution with prominent peaks around 300-325°C and 400-425°C; however, the relative height of the two peaks varies among samples. For a majority of samples, the second peak tends to be larger and more prominent than the first (Figure 3 and Figure S1). Because the temperature intervals for thermal fraction collection were identified based on thermogram evolution and shape, the intervals (i.e., F_1 to F_5) varied across samples (Figure 3).

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

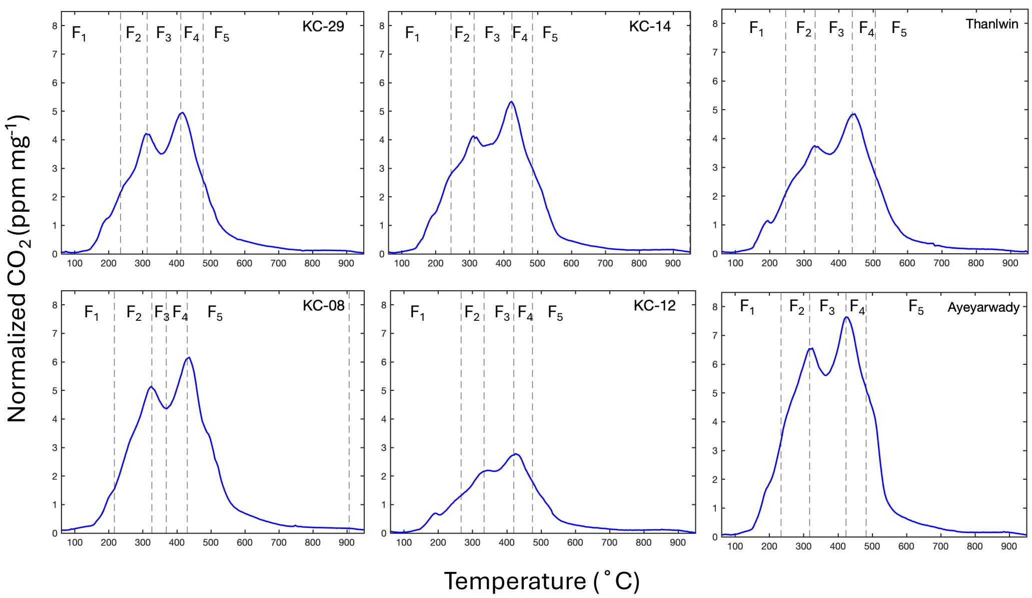

Figure 3. Example RPO thermograms from the Gulf of Martaban (KC-29), Martaban Depression (KC-08), "Mouths of the Ayeyarwady" (KC-14, KC-12), and the Ayeyarwady and Thanlwin Rivers. Temperature windows of CO_2 fractions are indicated by dashed lines with fractions denoted as F_1-F_5.

4.3 Isotope composition and activation energy distribution

The activation energy (E) distributions were determined for each sample using the rampedpyrox Python package by Hemingway et al. (2017b). Overall, there is minimal variation in the E distributions of all samples analyzed, with two prominent E peaks at ~140 and 160-170 kJ mol^{-1} and a long petrogenic tail starting around 200 kJ mol^{-1} (Figure 4). The mean E value does not vary greatly across samples ranging from 152.91 to 164.80 kJ mol^{-1} with an overall average of 160.07 kJ mol^{-1} and average standard deviation of 31.54 kJ mol^{-1}.

Isotopic compositions of sample fractions were averaged by depositional region for ease of spatial comparison (Figure 1 and 4). For all regions, the Fm of thermal fractions tends to decrease monotonously with increasing E, and the average Fm of all fractions from the "Mouths

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

of the Ayeyarwady" is consistently older than other regions (Figure 4). The average Fm of river sample fractions range from 0.60 to 0.94, while offshore sample fractions range from 0.51 to 0.95 (Figure 4). Average $\delta^{13}C$ values for river sample fractions range from -27.4‰ to -23.9‰ and offshore sample fractions range from -25.1‰ to -20.3‰ (Figure 4). The highest ^{13}C enrichment occurs at varying *E* across samples; however, majority of samples show enrichment in the third fraction, generally around 145-160 kJ mol^{-1} (Figure 4). The values for individual fractions from each sample as well as calculations of isotopic values for missing fractions can be found in Table S2 and Calculation S1.

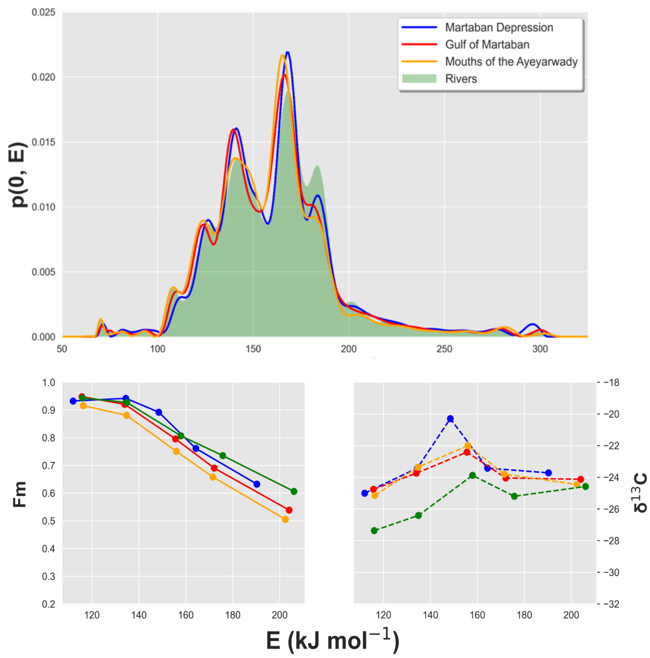

Figure 4. (Top) Average regional and river activation energy (*E*) distributions. Coring locations included in for the derivation of region averages can be found in Figure 1. Colored lines represent the regularized p(0,E) distribution over the continuum of *E* values, expressing the initial probability density function of *E* that results in the observed RPO thermogram (Hemingway et al., 2017b). The filled area indicates the average p(0,E) distribution for river samples. (Bottom) Average regional and river Fm and $\delta^{13}C$ isotopic compositions of RPO fractions plotted at the average *E* of the corresponding thermal window for the fraction.

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

4.4 Estimating terrestrial organic carbon content

The composition of offshore sediments is incompatible with a simple binary mixing of bulk fluvial OC and marine OC. Indeed, in a Fm vs. $\delta^{13}C$ diagram, nearly all offshore samples do not plot on the mixing line between bulk fluvial OC and marine OC (Figure 5). The only sample with an isotopic composition that plots on the bulk fluvial OC and marine OC mixing line is KC-05, located near the mouth of the Thanlwin. The initial fractions of this sample (KC-05) also exhibit the most depleted $\delta^{13}C$ of all offshore samples with similarly low E values to that observed in river samples (Table S2).

To estimate the proportion of TOC derived from terrestrial sources (hereafter TerrOC%) at all sample locations offshore we therefore use a binary $\delta^{13}C$ mixing model (Eq. 1) that employs sample-specific TerrOC end-members, derived from the isotopic composition of the river sample RPO fractions and a regionally applicable marine end-member.

Equation (1) $$\frac{(\delta^{13}\text{C Marine end−member}) - (\delta^{13}\text{C Observed})}{(\delta^{13}\text{C Marine end−member}) - (\delta^{13}\text{C Sample−Specific Terrestrial end−member})} = TerrOC\%$$

Sample-specific terrestrial end-members are identified by first deriving a fluvial OC mixing line from the isotopic composition (Fm and $\delta^{13}C$) of the A-T river sample RPO fractions, as this linear distribution expresses the continuum of diverse OC pools present within the fluvial end-member (Figure 5). On the fluvial OC mixing line, the river fractions with higher Fm and lower $\delta^{13}C$ that evolved at low *E* (<150 kJ mol^{-}1) represent younger, more labile biospheric TerrOC components (Hemingway et al., 2017b; Bao et al., 2018; Bao et al., 2019), while the fractions with increasingly reduced Fm and higher $\delta^{13}C$ that evolved at high *E* represent older, more recalcitrant TerrOC contributions such as pre-aged biospheric material (average *E* of fractions between 150 – 200 kJ mol^{-1}) and the potential inclusion of petrogenic material (average *E* of fractions >200-210 kJ mol^{-1}) (Rosenheim & Galy, 2012; Hemingway et al., 2017b; Bao et al.,

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

2019; Zhang et al., 2022). Overall, river sample RPO fractions on the fluvial OC mixing line range in Fm and $\delta^{13}C$ from 0.93 and -27.97‰ in the first fraction of the Ayeyarwady river sample (average E of 116 kJ mol^{-1}) to 0.56 and -23.70‰ in the fifth fraction of the Thanlwin River sample (average E of 210 kJ mol^{-1}) (Figure 5).

As the marine end-member was not sampled during the 2017 cruise, we estimate the $\delta^{13}C$ of the marine end-member to be -20.5‰ given marine stable isotopes values in the Andaman Sea (Fongtune & Duplessey, 1978; Fontugne & Duplessey, 1986). The Fm of the marine end-member is estimated to be ~1.0 as this aligns with the composition of dissolved inorganic carbon (DIC) in the Bay of Bengal (collected in 2016, Fm = 1.02; Raj & Kurian, 2024), and due to the fixation of DIC through primary production in the photic zone and regionally high particle sinking fluxes is likely representative of regional marine OC (Druffel et al., 1996; McNichol & Aluwihare, 2007; Krishna et al., 2024).

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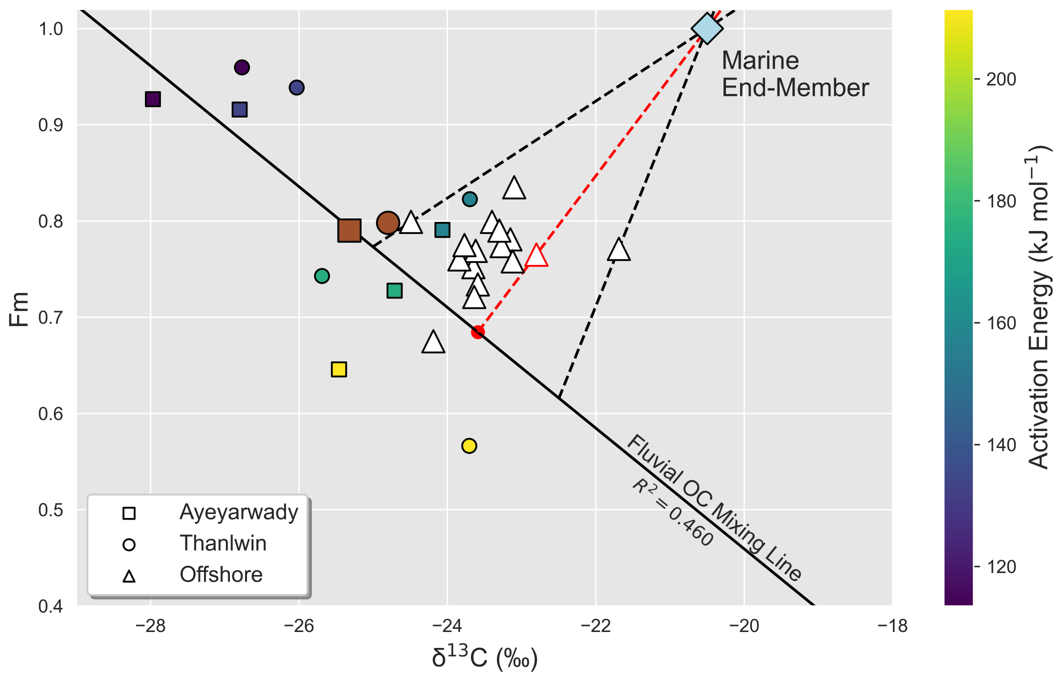
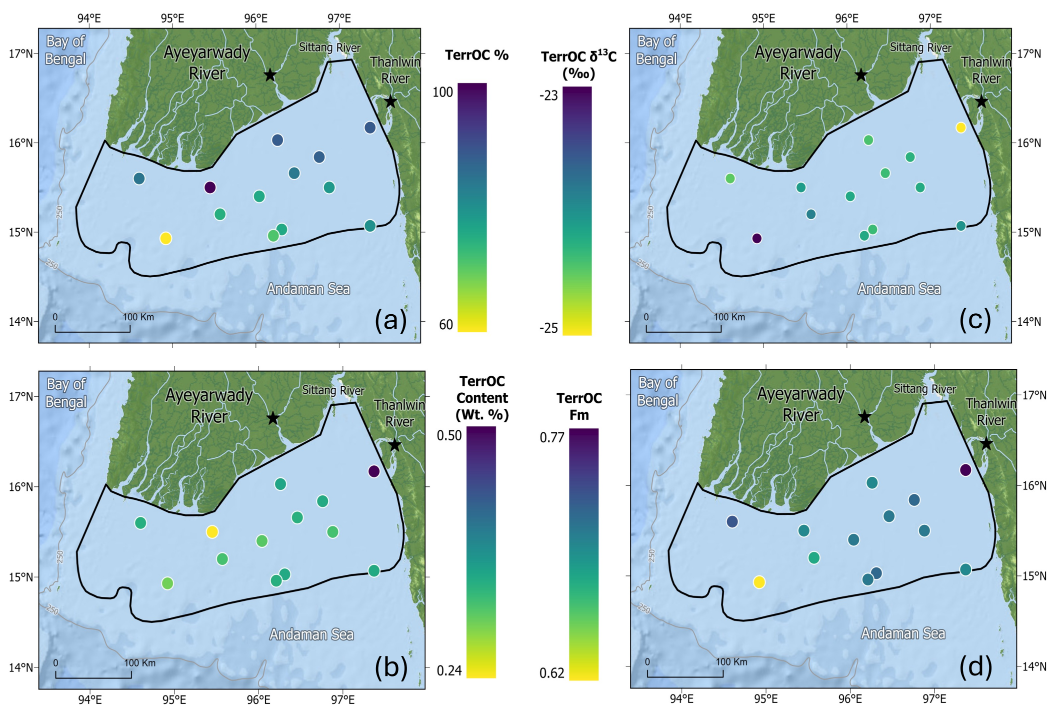


Figure 5. Isotopic compositions of bulk samples and river RPO fractions are shown plotted with fluvial OC and Terrestrial-Marine mixing lines. River bulk and RPO fractions are indicated in brown and *E* color-scale, respectively. Ayeyarway River samples are represented as squares and Thanlwin River samples are represented as circles. Bulk offshore samples are indicated by white triangles. The marine end-member is shown as a light blue diamond. The fluvial OC mixing line, derived from the linear regression of all river RPO fractions, is plotted as a solid black line. An example of a Terrestrial-Marine mixing line used to derive sample specific isotopic end-members is plotted as a red dashed line connecting the marine end-member to the fluvial OC mixing line, while intersecting the offshore sample outlined in red. The intersect of the Terrestrial-Marine and fluvial OC mixing lines is indicated by a red point, conveying the terrestrial end-member isotopic composition for the red-outlined offshore sample. The field of derived Terrestrial-Marine mixing lines is outlined by dashed black lines.

Assuming the offshore samples are a mixture of TerrOC and marine OC, Terrestrial-Marine mixing lines are then derived by preforming linear regressions between the discrete marine end-member and the bulk isotopic composition of each offshore sample. This linear relationship is then extended to intersect the fluvial OC mixing line, with the coordinates of the intersection

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

signifying the isotopic composition of the sample-specific TerrOC end-members. Sample-specific $\delta^{13}C$ end-members, which are found to range from -25.0‰ to -22.5‰, can then be applied to the binary mixing model to estimate TerrOC% at each offshore sample location (Figure 5 and Eq. 1). The estimated proportion of terrestrial material relative to TOC (i.e., TerrOC%) ranges from 60% to 100% across the Northern Andaman Sea shelf, demonstrating an across-shelf decrease. However, by using this proportion and accounting for sample and TOC mass to derive an absolute TerrOC content value (i.e., TerrOC Wt.%), the distribution becomes consistent from the Gulf of Martaban to the Martaban Depression (Figure 6). Similar to the distribution of TerrOC Wt.%, sample-specific TerrOC Fm and $\delta^{13}C$ (i.e., red point in Figure 5) indicate minimal spatial variation between the Gulf of Martaban and Martaban Depression, being consistently 0.72 $\pm$0.02 and 24.2‰ $\pm$0.3‰ (N=13), respectively (Figure 6).



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Preprint. Discussion started: 24 August 2026

Figure 6. Offshore distribution TerrOC isotopic composition and content. Spatial distribution of A) TerrOC% derived from the $\delta^{13}C$ binary mixing model is shown in comparison to B) TerrOC Content by Wt.% which is calculated from TerrOC%, TOC, and sediment sample weight. Isotopic compositions of sample-specific TerrOC end-members as derived from mixing lines in Figure 5 include C) $\delta^{13}C$ and D) Fm. The region of modern accumulation is indicated by the black polygon (Flynn et al., 2022) and Ayeyarwady and Thanlwin River sample locations are indicated as black stars.

5. Discussion

5.1 Terrestrial organic carbon distribution on the N. Andaman Sea shelf

Despite an apparent decrease in the proportion of TerrOC relative to TOC between the Gulf of Martaban and the Martaban Depression, the absolute TerrOC content and TerrOC end-member isotopic compositions are relatively uniform across the Northern Andaman Sea shelf suggesting that, after initial processing, a more recalcitrant / mineral-protected TerrOC pool remains largely unmodified between the Gulf of Martaban and the Martaban Depression (Rosenheim & Galy, 2012; Hemingway et al., 2019). The discrepancy in distribution between the proportion of TerrOC and absolute content can be attributed to an offshore increase in TOC via marine OC addition (Ramaswamy & Rao, 2014; Hossain et al., 2020). An increase in marine OC offshore is further supported by the increase in TOC, bulk Fm, bulk $\delta^{13}C$, and marine OC Wt.% (calculated from TOC, TerrOC%, and sediment sample weight) from the Gulf of Martaban to the Martaban Depression (Figures 2 and 7). Therefore, while marine OC varies spatially across the shelf, TerrOC content and composition remain fairly constant.

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Preprint. Discussion started: 24 August 2026

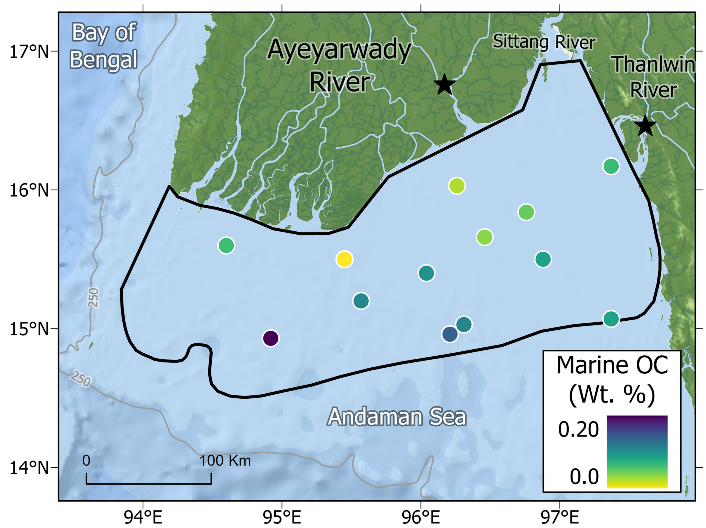

Figure 7. Marine OC Wt.% distribution for the Northern Andaman Sea shelf. The marine OC Wt.% is derived from the TerrOC% mixing equation, TOC mass, and sediment sample weight. The region of modern accumulation is indicated by the black polygon (Flynn et al., 2022). Locations of Ayeyarwady and Thanlwin River samples are indicated by black stars.

To further explore the distribution of TerrOC content across the Northern Andaman Sea shelf, we compare our estimates of offshore TerrOC Wt.% to that estimated in our Ayeyarwady (0.60 Wt.%) and Thanlwin (0.37 Wt.%) river end-member samples. Based on the average TerrOC Wt.% for the Northern Andaman Sea shelf (0.34 ±0.05 Wt.%) and the average TerrOC Wt.% for both rivers (0.48 ±0.16 Wt.%), we find that well over half of TerrOC observed in river samples (estimated to be around ~69%) is uniformly present on the Northern Andaman Sea shelf from the inner Gulf of Martaban to the mid-shelf Martaban Depression (Figure 8). A notable exception occurs at KC-05 near the mouth of the Thanlwin, where nearly all of the TerrOC content from the river samples is observed. KC-05 also exhibits isotopic compositions of initial RPO fractions most similar to that of river samples, suggesting the presence of labile fluvial material (Table S2). Together, these observations indicate that the remineralization of labile TerrOC occurs nearshore, while TerrOC content remains consistent across the shelf, despite

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

high-energy conditions that facilitate seabed mixing and the potential oxidation of terrestrial material. To consider the implications of hydrodynamic sorting on TerrOC distribution, we normalize TerrOC Wt.% in river and offshore samples to Al/Si ratios for the river end-member samples and gravity cores previously analyzed by Flynn & Kuehl (2025). While the availability of directly comparable Al/Si data precludes us from conducting this normalization for all offshore samples, it is evident that locations proximal to river mouths maintain higher TerrOC content, while the mid-shelf exhibits minimal spatial variation (Figure 8). This indicates that hydrodynamic sorting does not exert primary control over the distribution of TerrOC on the shelf, and thus our identification of high potential for offshore accumulation in the mid-shelf depocenter is instead driven by the selective preservation of refractory material following resuspension and transport on the shelf.

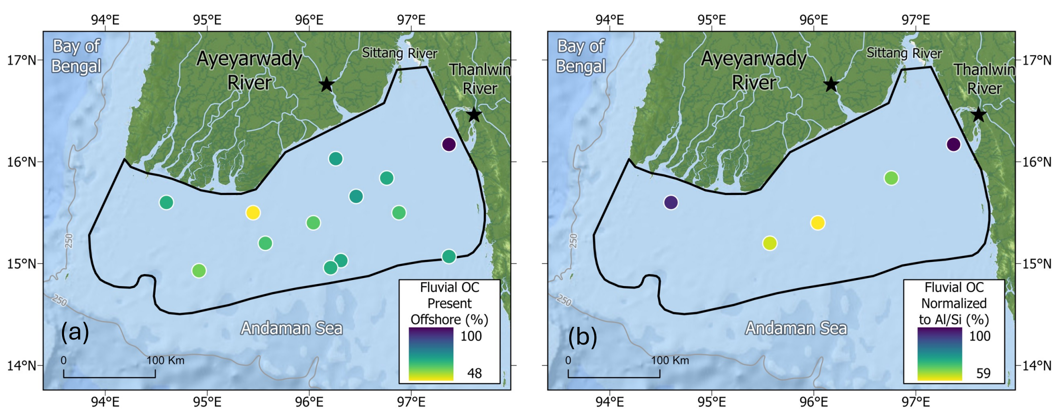

Figure 8. (a) The percent of TerrOC (Wt.%) identified at the A-T river mouths present at offshore coring locations across the Northern Andaman Sea shelf and (b) the percent of TerrOC (Wt.%) identified at the river mouths present offshore normalized to Al/Si. Al/Si ratios are from gravity cores collected by Kuehl et al. (2019) and analyzed using XRF methods by Flynn & Kuehl (2025).

A comparison of TerrOC content and normalized excess ^{210}Pb inventories on the shelf also highlights the minimal propensity for TerrOC remineralization during shelf transport. Flynn et al.

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

(2025) observed spatially consistent normalized excess ^{210}Pb inventories across the Northern Andaman Sea shelf, which is attributed to the substantial advection of ocean water onto the shelf along with intense tidal mixing in the Gulf of Martaban. This produces long water-column residence times and thus increased oxygen exposure for terrestrial material. Therefore, while increased oxygen exposure time in mobile muds in other high energy deltas has been postulated to increase remineralization of terrestrial material (Aller, 1998; Aller & Blair, 2006; Bianchi et al., 2018), the minimal variation (0.26-0.50 Wt.%) in TerrOC content from the Gulf of Martaban to the Martaban Depression that we observe in this study paired with previous findings of long water column residence time, indicates that substantial resuspension and re-exposure to ocean water during transport does not facilitate the remineralization of TerrOC on the Northern Andaman Sea shelf (Figure 9).

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Preprint. Discussion started: 24 August 2026

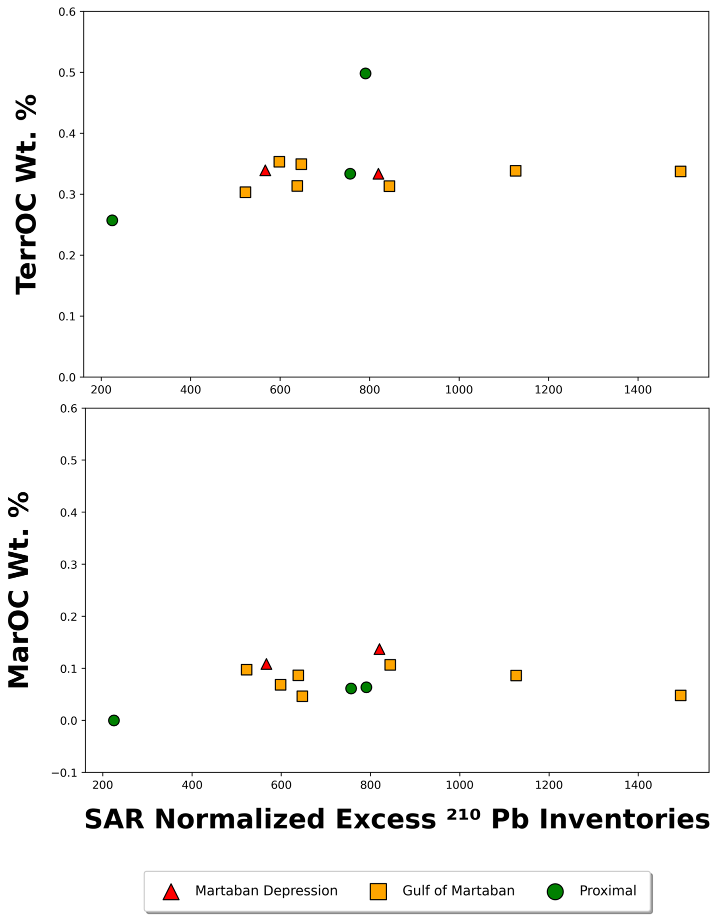

Figure 9. TerrOC Wt.% and marine OC (MarOC) Wt.% plotted relative to sediment accumulation rate normalized excess ^{210}Pb inventories for the Northern Andaman Sea shelf. Data for normalized inventories has been reported previously by Flynn et al. (2025). OC content is plotted by region including cores from the Gulf of Martaban (orange), Martaban Depression (red), and locations KC-05, KC-02, and KC-12 proximal to the river mouths (green).

Given the lack of evidence for offshore remineralization, it is likely that physical and / or microbial remineralization processes control the degradation of the most labile fluvial TerrOC components in the A-T river distributary mouths and / or near-shore environment prior to offshore accumulation (Goosen et al., 1999; Klinkhammer et al., 2000; Herfort et al., 2017).

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

Microbially, changes in the diversity and / or abundance of microbial communities where saline and freshwater bodies mix may result in increased TerrOC processing as heterotrophy becomes dominant at estuarine turbidity maximums (Ziervogel & Arnosti, 2009; Herfort et al., 2017; Smith et al., 2017). Additionally, physical estuarine-like processes, such as deposition and resuspension cycles driven by tidal and density currents, may impact coastal remineralization and episodically transport processed TerrOC offshore through tidal and seasonal hydrodynamic fluctuations (Glover et al., 2021; Anthony et al., 2022). While during low discharge physical and microbial remineralization processes likely occur within the distributary mouths as marine waters are advected landward, periods of high discharge likely force the salinity front into the coastal ocean causing the spatial extent of coastal remineralization to vary seasonally (Ramaswamy et al., 2004; Glover et al., 2021). Nonetheless, our offshore sampling results indicate that active TerrOC remineralization is spatially constrained to the fluvial and nearshore regions, whereas resuspension and transport via fluid muds and the SML on the middle and outer shelf have a limited effect on TerrOC degradation.

These findings are in contrast to previous studies of the offshore delta that have identified a decrease in TerrOC Wt.% by as much as 30% from the Gulf of Martaban to the Martaban Depression (Flynn et al., 2022; Flynn & Kuehl, 2025). This discrepancy can be explained from the assumption that bulk river end-members are fully representative of the TerrOC accumulating in offshore deposits. This assumption ignores the complex reactivity and stability of OC pools, which are remineralized at different rates and extents during transport across the shelf. In this study, offshore TerrOC isotopic signatures, derived from RPO sample specific isotopic end-members (Figure 5), were found to be older and more ^{13}C enriched than the bulk Fm and $\delta^{13}C$ values observed in the A-T river sediments. Instead, offshore TerrOC isotope composition

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

closely resembles that of the pre-aged biospheric TerrOC components, being older and ^{13}C enriched, identified in river sample RPO fractions collected at E >150 kJ mol^{-1} (Hemingway et al., 2017b) (Figure 5). This indicates that the most labile biospheric components (characterized by a relatively younger radiocarbon age and depleted ^{13}C signature) of the bulk fluvial TerrOC pool (i.e., E <150 kJ mol^{-1}) are preferentially remineralized prior to accumulation in shelf sediments, effectively preventing bulk river end-members from being representative of offshore TerrOC.

5.2 Organic carbon characteristics in proximal and distal shelf settings

While TerrOC content and isotopic composition is relatively consistent from the Gulf of Martaban to the Martaban Depression, we find that coring locations proximal to the river mouths have the highest terrestrial influence, while distal locations on the shelf exhibit increased marine influence. Both KC-05 near the mouth of the Thanlwin and KC-14 near the "Mouths of the Ayeyarwady" exhibit signatures of the adjacent river mouth through terrestrial isotopic compositions and high TerrOC content (Figure 6). High TerrOC Fm and low TerrOC $\delta^{13}C$ composition in both KC-05 and KC-14 also indicate the presence of younger, biospheric TerrOC relative to other coring locations on the shelf (Figure 6). Liu et al. (2020) also observed high concentrations of lignin phenols and relatively low vanillyl acid / aldehyde ratios at KC-14, suggesting the deposition of relatively undegraded terrestrial organic carbon near distributary mouths.

In contrast to KC-14, the lowest SA, TOC, and TerrOC Wt.% values on the Northern Andaman Sea shelf are observed in KC-12, revealing a pronounced grain size effect proximal to the "Mouths of the Ayeyarwady" (Figure 2 and 6, Table S1). This pattern may be explained by the presence of a nearshore mud belt at KC-14 and the potential for increased winnowing via

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

coastal currents at KC-12 (Kuehl et al., 2019) and suggests that the presence of coarse material largely controls the low TerrOC content (Mayer, 1994; Hedges & Keil, 1995; Blair & Aller, 2012). This grain size effect also likely produces an underestimation in the calculation of the percent ratio of TerrOC in river to offshore samples at KC-12 (Figure 8), as based on the Terrestrial-Marine mixing line and bulk isotopic compositions 100% of the TOC in KC-12 is attributed to terrestrial sources.

Located at the most seaward portion of our study area, TerrOC isotope compositions of KC-24 suggest that terrestrial material is the oldest and most refractory of that observed (Figure 6). Previous studies have suggested that relict and sandy material dominates this distal shelf region, which would support the findings of older, refractory TerrOC (Rao et al., 2005; Kuehl et al., 2019; Liu et al., 2020). Additionally, the proportions of marine and terrestrial OC components at KC-24 are more similar, producing the lowest TerrOC% on the shelf of just 60% (Figure 6). By comparison, marine OC Wt.% is the highest in this distal shelf setting (Figure 7), demonstrating an increase in marine influence closer to the shelf break.

Proximal to distal variations in TerrOC character on the shelf can also be shown through bulk N/OC and $\delta^{13}C$ values. Utilizing the carbon and nitrogen dataset produced by Flynn & Kuehl (2025) for the same suite of sediment cores from the offshore delta and the A-T river carbon and nitrogen dataset from Bird et al (2008), we observe two distinct mixing lines that are characteristic of proximal OC processing followed by mixing with distal marine OC sources (Figure 10). River and proximal sites are observed along the first mixing line as indicated by a transition between depleted ^{13}C with low N/OC values, associated with fresher terrestrial material in rivers, to slightly enriched ^{13}C with higher N/OC values, characteristic of degraded TerrOC. The second mixing line can be observed between proximal locations and the distal shelf

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

as ^{13}C, and N/OC signatures are indicative of mixing between the degraded TerrOC in proximal samples and marine OC sources (Figure 10). These findings also align with the bulk carbon and nitrogen data collected within this study (Figure 10), further emphasizing that the degradation of labile TerrOC likely occurs within proximal, near-shore locations on the shelf, whereas degraded TerrOC is selectively preserved during shelf transport and becomes increasingly mixed with marine OC sources on the distal shelf.

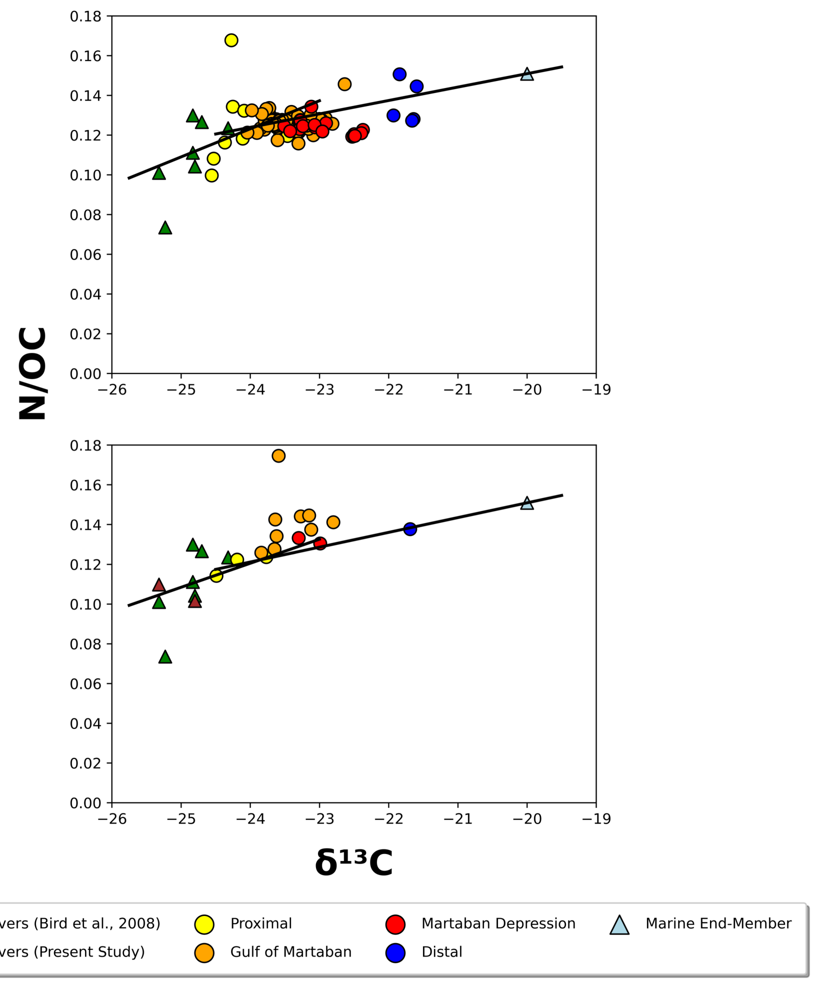

Figure 10. Bulk N/OC and δ^{13}C values from (top) Flynn & Kuehl (2025) and (bottom) the present study. Bulk offshore compositions are plotted as circles and grouped by region including locations proximal to river mouths (yellow), Gulf of Martaban (orange), Martaban Depression

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

(red), and distal locations on the shelf (blue) including KC-24 from this study and KC-13 and KC-24 from Flynn & Kuehl (2025). A-T river values presented in this study are indicated by brown triangles. The marine end-member (light blue triangle) indicates regional values for marine OC as reported by (Fontugne & Duplessy, 1978), while the Bird et al. (2008) A-T river values document the literature fluvial end-member (green triangle). Mixing lines were plotted using average river mouth, proximal, and marine OC compositions as applicable end-members. River samples and proximal samples are shown to follow a mixing line of increasingly degraded TerrOC resulting in a mixing line with a greater slope, while Gulf of Martaban, Martaban Depression, and distal locations demonstrate a mix between degraded TerrOC and increasingly marine OC sources producing a mixing line with a reduced slope.

5.3 Global comparisons in offshore terrestrial organic carbon burial

The previous underestimation of offshore TerrOC content in large subaqueous deltas, such as that described in this study, has substantial implications for understanding the fate of TerrOC in the ocean. Oxygen exposure time in mobile muds is postulated to be a primary controlling factor on TerrOC remineralization across the continental shelf (Aller & Blair, 2006; Blair & Aller, 2012; Bianchi et al., 2018). While we do find evidence for marine OC degradation in the Gulf of Martaban, our results indicate that biogeochemical processes occurring nearshore and within distributary mouths likely facilitate the remineralization of labile TerrOC while more refractory TerrOC components are dispersed offshore.

In the case of the Amazon River Delta, previous bulk stable isotope analyses have estimated that TerrOC loading is significantly reduced along the ~1600 km Amazon-Guianas mobile mudbank system, with a burial efficiency of only ~30% (Shower & Angle, 1986; Hedge & Keil, 1995; Aller, 1996; Aller & Blair, 2006). In contrast, more recent RPO and radiocarbon studies have found that TerrOC preservation in the mudbanks is substantially higher when the refractory nature of offshore TerrOC is considered (William et al., 2015; Boehman, 2025). Based on radiocarbon, William et al. (2015) estimated that burial of refractory terrestrial material is 6% higher than previous estimates. While this may appear minimal, it represents a reduction of ~0.5

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

Tg C y^{-1} of CO_2 released to the atmosphere via remineralization (Williams et al., 2015). Assuming that the preservation of refractory TerrOC has been underestimated in the Amazon mudbanks, as well as offshore of the A-T rivers, it is probable that energetic offshore delta systems provide a significant carbon sink despite the potential for oxidation through frequent resuspension.

While the preservation of pre-aged refractory TerrOC may be higher than previously expected offshore of these large delta systems, RPO studies offshore of the Yangtze River Delta still support that long distance shelf transport has the capacity to age and degrade some portion of refractory TerrOC through extended lateral transport time, hydrodynamic sorting, and oxygen exposure (Bao et al., 2018; Bao et al., 2019). In this context, the lack of change in TerrOC Wt.% and isotopic composition across the Northern Andaman Sea shelf may be attributed to a relatively short transport distance to the primary depocenter (<200 km from the head of the Gulf of Martaban, compared to upwards of 800 km from the mouth of the Yangtze; Liu et al., 2007; Xu et al., 2012). Due to the regional oceanographic conditions, A-T sediment delivered to the Gulf of Martaban is trapped within the funnel-shaped Gulf and thoroughly mixed via tidal currents (Fair, 2021; Harris et al., 2022), resulting in spatially homogenous TerrOC isotopic signatures. Based on excess ^{210}Pb profiles from the clinoform foresets, material from the Gulf of Martaban is likely episodically released to the Martaban Depression on tidal and / or seasonal timescales (Flynn et al., 2025), facilitating minimal transport time and extending the homogeneity of isotopic signatures from the inner-middle shelf to the primary depocenter. Moreover, because the majority of the sediment in the Gulf of Martaban exhibits relatively similar grain size, being consistently fine silt and clay (<20 μm), sediment transport likely occurs at a consistent rate with little impact from selective degradation associated with hydrodynamic

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

sorting (Bao et al., 2018). Unlike the Yangtze and other long shelf transport systems, we would expect the rapid shelf transport of fine grain sediments to limit potential remineralization of refractory TerrOC between the Gulf of Martaban and the Martaban Depression. This would allow for the high observed TerrOC content to persist across the Northern Andaman Sea shelf, despite highly energetic oceanographic conditions. With the Ayeyarwady being one of the world's largest delta systems, high connectivity between the Gulf of Martaban and Martaban Depression and the resultant high TerrOC content in the primary offshore depocenter suggests that burial of TerrOC is much more effective than previously suggested on this high-energy, river-dominated margin.

6. Summary and conclusions

This study investigated TerrOC processing and dispersal in the offshore Ayeyarwady Delta through the use of RPO methods and provides a new conceptual framework for TerrOC accumulation in sediments along high-energy, river-dominated margins. In summary, our findings suggest that refractory TerrOC is selectively preserved following shelf transport, driving uniform distributions and higher content than previously estimated. The isotopic composition of bulk offshore samples exhibits lower Fm and enriched ^{13}C compared to bulk river end-members, with TerrOC isotopic signatures of offshore samples aligning more consistently with river sample RPO fractions evolved at E >150 kJ mol^{-1}. This indicates that terrestrial material accumulating on the shelf is composed of more refractory, pre-aged biospheric and potentially petrogenic TerrOC components. The relatively consistent TerrOC content and refractory TerrOC isotopic compositions across the Northern Andaman Sea shelf further suggests that remineralization of the labile TerrOC components must occur prior to shelf transport, likely occurring coastally within distributary mouths and / or in the near-shore environment through

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

physical and / or microbial processes associated with the mixing of fresh and saline water bodies. The short transport time across the Northern Andaman Sea shelf may limit the remineralization of refractory TerrOC components as other large river deltas with extensive shelf transport regimes, such as the mobile mud area offshore of the Yangtze and Amazon Deltas, have demonstrated the propensity to age and degrade even refractory TerrOC components. By assessing the isotopic character of TerrOC and comparing RPO-derived TerrOC content on the Northern Andaman Sea shelf to that derived from bulk stable isotope analyses we demonstrate that TerrOC has been substantially underestimated in this large deltaic system due to the presence of refractory material previously not captured by bulk measurements. This has significant implications for estimating global carbon burial, as sedimentary TerrOC preservation at some of the world's largest TerrOC point sources is likely much higher than previously suggested.

Data availability

RPO and isotope data used for estimation of TerrOC content and characterization in this study is available through William & Mary via doi.org/10.25773/g7zk-sg96 and is also presented in the Supporting Material. The open-source "rampedpyrox" package utilized for data analysis can be accessed using the Python Package Index (Hemingway, 2017, https://doi.org/10.5281/zenodo.839815, http://pypi.python. org/pypi/rampedpyrox) with usage detailed by Hemingway et al. (2017b).

Author contributions

https://doi.org/10.5194/egusphere-2026-4612
Preprint. Discussion started: 24 August 2026

Evan R. Flynn: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft **Valier Galy**: Conceptualization, Methodology, Writing – Review & Editing **Steven A. Kuehl:** Conceptualization, Methodology, Writing – Review & Editing, Funding acquisition **Manuel Colombo**: Methodology, Writing – Review & Editing

Competing interest

The authors declare that they have no conflict of interest.

Statement on inclusion in global research

This study was conducted in close collaboration with faculty, staff and students from Mawlamyine University and the University of Yangon. Our Myanmar colleagues participated in the field work, a group visited the US as part of outreach and training, they were included as co-authors in a number of publications and meeting abstracts and participated in the 2025 EGU annual meeting. Furthermore, an international workshop was held at the University of Yangon to communicate the results of the study and was augmented by additional training for students and staff.

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