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ViewPoints

Flood discharges of a small river into open coastal waters: Plume traits and material fate

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Abstract

The dynamics of plumes from large rivers are relatively well known. Many estuaries are small, however, and discharge directly onto exposed, open shorelines and presumably produce smaller plumes that may have different properties. Therefore this study measured traits of a small estuary on the Australian East Coast as a model system, focusing on (a) plume size, (b) distinctness of plume edges, and (c) imprints on the seafloor. Although plumes were found to be limited in spatial extent (ca. 1 km offshore × 2.4 km longshore) and were constrained near the shore by onshore winds, they exported high nutrient loads from an urbanised watershed. The small plumes were shallow (<2 m) and strongly buoyant, with sharp vertical and horizontal clines similar to much larger plumes. The edges of the plumes were highly distinct, clearly separating disparate water masses that trapped significantly higher amounts of nutrients inside the plume. Some particulate material exported from the estuary in the plumes reached the benthos of the nearshore zone, as evidenced by increases in copper concentrations in sediments under the plume. By contrast, the amount of land-sourced carbon delivered by small plumes to the seafloor was minor in comparison to larger inputs from marine sources (e.g. onshore advection of phytoplankton blooms or algae dislodged from reefs) that swamped any contribution from plumes. Overall, small plumes can be important in land–ocean coupling, but their zone of influence may be limited.

Keywords: Australia; estuary; heavy metals; river; stable isotope analysis

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1. Introduction

Rivers and estuaries often discharge in the form of plumes, which act as conduits for the export of sediments, nutrients, and organic material from land to the oceans (Furnas et al., 1995; Rabalais et al., 2000). Plumes are often buoyant, spatially confined, and characterised by sharp clines in salinity and turbidity (Grimes and Kingsford, 1996). Plumes are areas of enhanced biological processes in the pelagos (Devlin et al., 2001), and modify the benthos via precipitation of particulate matter (Alliot et al., 2003).

Plumes have mostly been studied for large rivers (e.g. Mississippi, Amazon) that deliver high loads of nutrients and deposit organic material over large areas of the shelf (Smith and Demaster, 1996; Alongi, 1998; Lohrenz et al., 1999; Rabalais et al., 2000). Plume traits may, however, not scale down linearly from larger systems in situations when small rivers discharge directly onto exposed shorelines. Such small estuaries on open coastlines are common in most of Australia and South Africa (Eyre, 1998; Harrison, 2004). In addition to estuarine size (and presumably plume size), the discharge characteristics of such small estuaries may also differ from larger rivers. In Australia, freshwater flow in 70% of estuaries is in the form of episodic, short-lived, but large, freshwater spikes that occur mostly during the austral summer (Eyre, 1998).

Given the paucity of data on plumes from small estuaries that discharge directly onto open shorelines not bounded by bays or offshore islands, we targeted such small plumes and quantified three key properties: (1) the spatial extent of small plumes, (2) the concordance between visually sharp plume

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boundaries and chemical differences of water masses, and (3) possible plume imprints on the seafloor.

2. Methods

Small plumes were studied off the Mooloolah estuary, SE Queensland, Australia (Fig. 1). The estuary is small (catchment 194 km^2), shallow (1–5 m) and short (tidal reaches 13 km; Schlacher et al., 2005). It discharges directly onto an exposed coast through a narrow and shallow mouth (ca. 3 m deep × 80 m wide). Because significant river discharge along this coast occurs mostly during the austral summer in the form of distinct spikes (Eyre, 1998), sampling concentrated on the rainy season during the austral summer and autumn of 2002/2003 that included several rainfall pulses.

The spatial extent of surface plumes was determined from physical sampling of the water column (CTD casts of salinity, temperature, turbidity and isotopic and elemental signatures – δ^{13}C, δ^{15}N, %C, %N – of suspended organic particles), complemented by aerial surveys in light aircraft. We contrasted conditions after the largest rainfall spike during the rainy season of 2002/2003 (10 February 2003, river discharge 1500 ML day^{-1}, rainfall 95 mm) with "low-flow" conditions (20 December 2002, river discharge <100 ML day^{-1}, no rainfall in preceding fortnight). Water samples were taken at 22 sites chosen from visual assessments by observers in boats and in aircrafts overhead. To determine the properties of plume edges, vertical profiles of water chemistry and physics were recorded at 10 sites distributed inside the plume and just seawards of the plume's edge (Fig. 1c). Seafloor imprints of plumes were assessed from sediment collections at 24 sites (Fig. 1a), comprising sets taken before (13 and 20 December 2002) and after (31 December 2002, 14 January 2003) a significant discharge event.

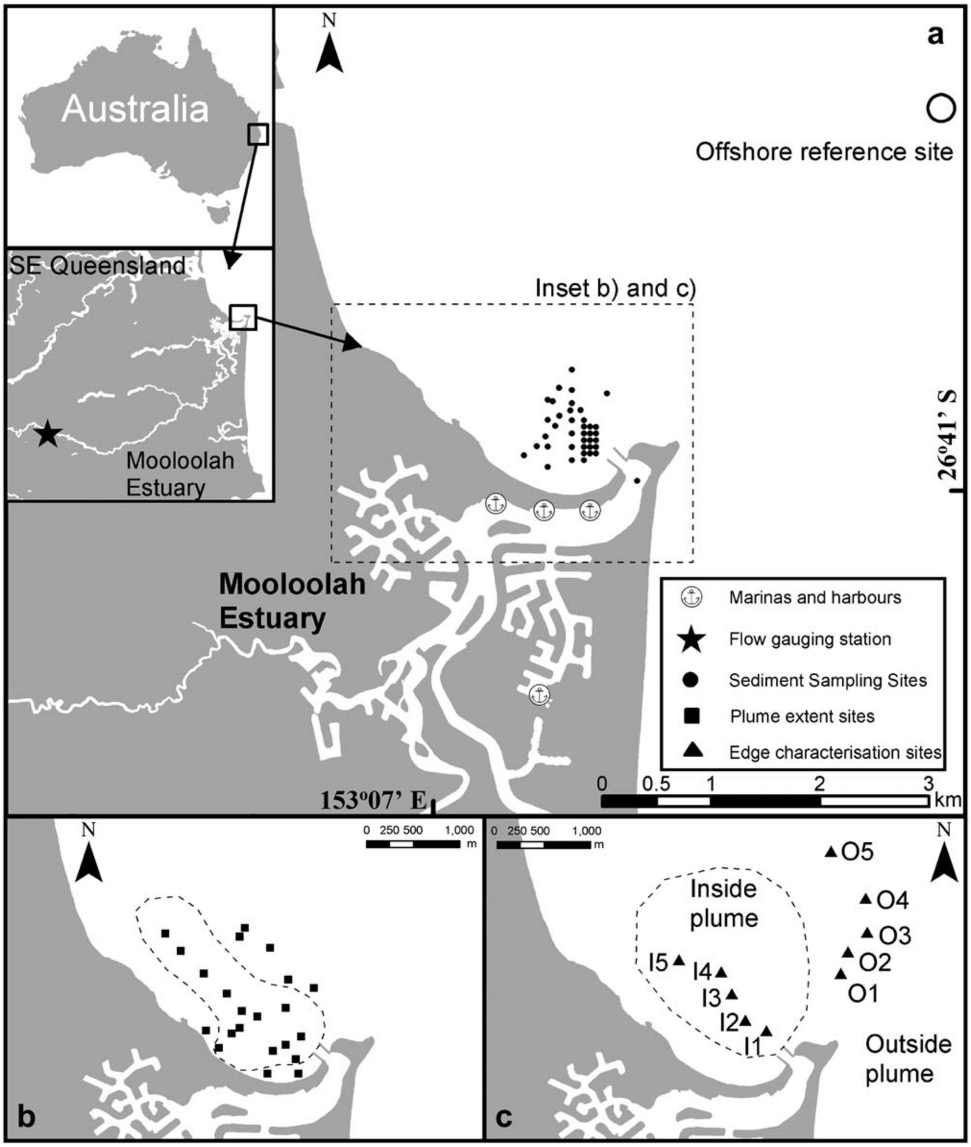

Fig. 1. The Mooloolah estuary showing sampling location for (a) sediment mapping, (b) plume extent, and (c) edge characteristics. The approximate spatial extent of plumes, estimated from CTD casts and visual observations, is represented by the dotted line in (b) and (c).

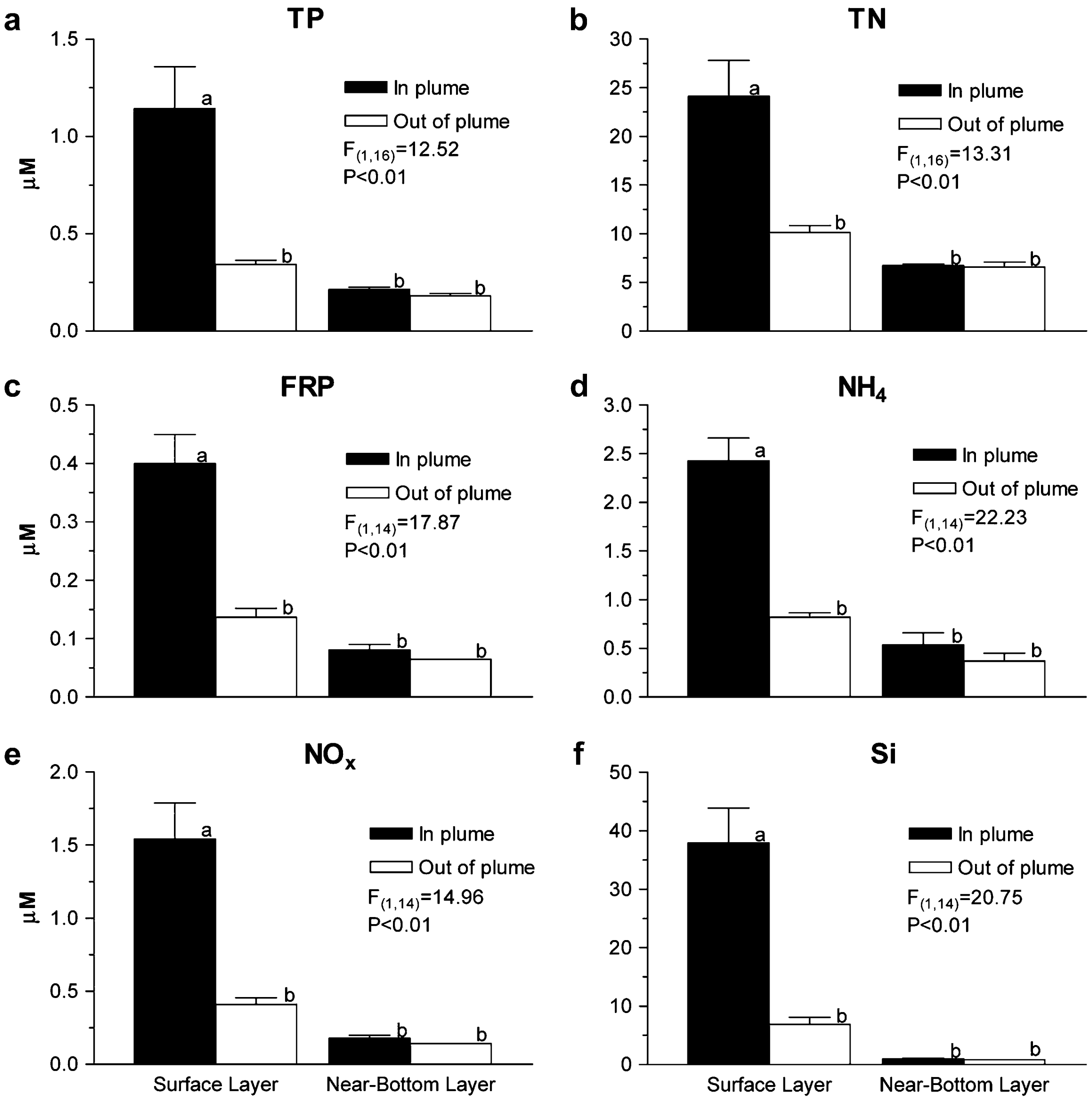

Fig. 2. Nutrient characteristics of the Mooloolah estuary plume sampled on May 17, 2003, highlighting concentrations inside and outside in the surface and near-bottom layers. (Bars with similar letters indicate no significant difference of means by post hoc testing following ANOVA).

We traced the provenance of organic matter (e.g. marine vs. estuarine) in plumes with stable isotopes (δ^{15}N, δ^{13}C), using known isotopic differences between terrestrial and marine plants (Peterson and Fry, 1987; Schlacher and Wooldridge, 1996). Samples of suspended POM and organics in sediments were decalcified and analysed on an Isoprime mass spectrometer with a precision of 0.2‰. Copper concentrations in sediments were analysed with a Perkin Elmer AAS (Analyst 800 model, detection limit of 0.01 mg/kg for Cu).

3. Results

The rainfall pulse of 10 February 2003 (peak river flow: 17.6 $m^3\,s^{-1}$) produced a distinct plume. The plume extended for 1.1 km offshore, had a maximum distance along the coast of 2.4 km, and encompassed an area of 1.7 km^2 (Fig. 1). Strong onshore northerly winds during the survey confined the surface plume to a position near the shoreline (Fig. 1). Sharp horizontal and vertical gradients characterised the plume: (a) surface salinity at the estuarine inlet decreased from 35.7 to 30.0 after rainfall, but salinity was near oceanic 1.7 km from the estuary mouth, and (b) vertically, the plume was a thin and buoyant water mass (e.g. at 1 m depth, rainfall did not alter the salinity values at the estuarine mouth). Biochemical (C:N) and isotopic (δ^{13}C) characteristics of particulate matter in the nearshore zone shifted significantly following rainfall. Material suspended in the plume had a significantly lower C:N ratio (plume: 5.61 ± 0.09 vs. base-flow: 6.21 ± 0.09; $t = 5.5$, $P_{(2)} < 0.001$), and δ^{13}C isotope ratio (plume: −22.66 ± 0.10 vs. base-flow: −21.76 ± 0.08; $t = 7.10$, $P_{(2)} < 0.001$).

The distinct visual boundaries of the plume (judged from contrasts in surface water colour) were mirrored by distinct differences in the chemical composition between water masses. Outside the plume, salinity (34–36) and turbidity (0 NTU) were homogenous throughout the water column. Inside the plume, salinities dropped to 22 in the top 2 m of the water column, but remained at 34–36 deeper than 2 m. Turbidity ranged

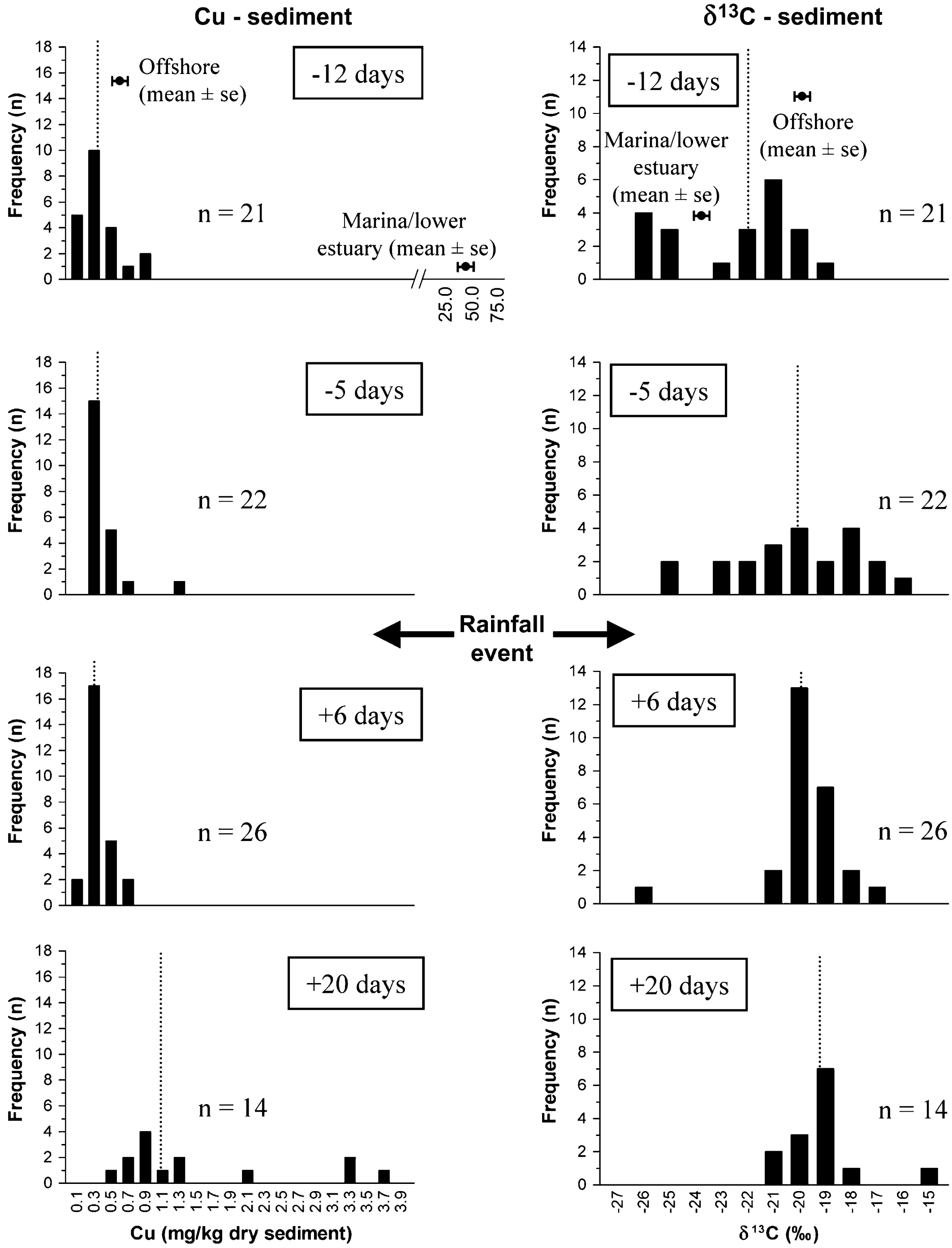

Fig. 3. Frequency histograms of Cu (left side panels) and δ^{13}C (right side panels) in sediment samples at 12 and 5 days before rainfall, and 6 and 20 days following rainfall. The mean ± SE of Cu and δ^{13}C for offshore reference values and marina/lower estuary are presented in the top panels, respectively. The median value for each date is represented by the dotted line.

up to 20 NTU to a depth of 3 m. All nutrient species showed the same pattern of significantly higher concentrations in surface layers inside the plume. This sharp contrast in nutrient levels between water masses was confined to the top layer of the water column; nutrient levels in the near-bottom layer did not differ inside and outside the plume (Fig. 2).

Plumes produced a distinct imprint on the seafloor. Concentrations of copper in sediments below the plume increased threefold following a freshwater discharge spike (ANOVA $F_{(3,78)} = 19.19, p < 0.01$; Fig. 3), but this Cu increase had a distinct time-lag: 6 days after the flow event, sediment-Cu in the putative plume remained similar to base-flow conditions and offshore reference values (Fig. 3). However, 3 weeks after the flow event, strongly elevated levels of Cu in sediments were recorded under the plume area (up to 800 m from the estuarine inlet; Fig. 3). Carbon isotope ratios of sediments under the plume became more enriched following rain (before δ^{13}C: $-22.5 \pm 0.5‰$, after δ^{13}C: $-19.1 \pm 0.4‰$, $F_{(3,78)} = 9.89$, $p < 0.01$; Fig. 3). This isotopic shift in δ^{13}C values began, however, prior to the onset of the plume and continued throughout and after the plume event (Fig. 3). The range of δ^{13}C values also decreased over the survey period from a wider dispersion before the plume to a narrow range following the flow event (Fig. 3).

4. Discussion

Whereas the role and dynamics of plumes from large rivers is relatively well known, the nature and scale of influence of small estuarine plumes has not been documented. We studied an example of the numerous small estuaries discharging onto open coastlines around the world, and found that plumes are strongly buoyant, have sharp boundaries, and extend only a short distance offshore. Estuarine plumes have been reported ranging in size from tidally driven plumes of 2–11 km (Kingsford and Suthers, 1996) to plumes over 100 km long associated with major rivers (Curtin, 1986). We recorded even smaller plumes, no more than 2.4 km in length and extending <2 km offshore. The size of small plumes is thought to be more variable, principally governed by wind regimes and river discharge (Devlin et al., 2001). Under calm conditions, even plumes from small estuaries can disperse seaward over much of the continental shelf (Devlin et al., 2001), but in the present study persistent north-easterly winds during the development of the plume retained the plume near the shore. The strong horizontal and vertical gradients of salinity and turbidity in this small plume are consistent with those recorded in plumes of all sizes (Grimes and Kingsford, 1996).

Nutrient concentrations increased several-fold (240–550% over base-flow values) in this small plume. Nitrogen levels in the plume from the Mooloolah estuary broadly match or were higher than levels reported from larger estuarine systems along the Queensland coast where a large fraction of the catchment has been cleared for agriculture (Devlin et al., 2001). High nutrient export in the Mooloolah plume might result from large-scale urbanisation of the lower catchment where almost all natural habitats (mangroves) have been transformed into canal estates that drain directly into the estuary through numerous stormwater pipes (Schlacher and Carruthers, 2002). Thus, even a relatively small plume can export high nutrient loads to nearshore waters if it drains a highly disturbed watershed.

Organic carbon from terrestrial sources is relatively refractory (Schlacher and Wooldridge, 1996) and can thus accumulate in the sediments under plumes (Dagg et al., 2004). We observed that plumes carry terrestrial material as suspended particles (based on depleted δ^{13}C values of SPOM), but this material apparently did not reach the seafloor below the plume. On the contrary, the δ^{13}C signature of sediments under the plume shifted towards a stronger marine signal. Importantly, however, we detected this shift towards a marine isotopic signature before the plume had developed. This suggests that changes in the sedimentary carbon pool by marine imports are decoupled from plume events. We also observed smaller spatial variability in the isotope signal after the initial shift, suggesting that the sedimentary carbon pool was swamped by large-scale imports of carbon related to wind or other environmental factors at sea. A possible source of the marine carbon could be blooms of the marine cyanobacteria *Trichodesmium* spp. that drifted into the plume area. They are an important component of the subtropical plankton and regularly bloom along the Queensland coast during the summer (Furnas, 1992), and their carbon isotope signatures are light (δ^{13}C: -15.2 to $-11.9‰$; Carpenter et al., 1997). Thus, the δ^{13}C values in sediments found under the plume could have been shifted towards more positive values when slicks of *Trichodesmium* were blown onshore by north-easterly winds during the study and settled in the plume area. Another possible source of marine carbon to plume sediments are macroalgae from reefs. Local species of marine macroalgae have enriched δ^{13}C values (median δ^{13}C of six species: $-17.9‰$; TA Schlacher, unpublished data). During rough sea conditions, macroalgae are regularly ripped from offshore reefs and are transported onshore where they form substantial wrack deposits on beaches abutting the plume (TA Schlacher, personal observation).

Concentrations of copper in sediments were elevated under the plume. Copper is a common contaminant associated with boats, and there are numerous private boat moorings, and several harbours and marinas in the lower Mooloolah estuary (Schlacher and Carruthers, 2002). Indeed, copper concentrations in sediments inside the marinas and boat basins of the Mooloolah estuary are very high (>140 mg kg^{-1} DW, T Gaston, unpublished data), forming a putative source of contaminants available for export by plumes. The observed time-trajectory of copper seawards of the estuary suggests that plumes can transport contaminated sediments to sea where they form a seafloor imprint of export activity; copper may thus be a conservative tracer of such small plumes.

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