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News & views

Marine biogeochemistry

Trace elements in the ocean go bottom-up

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The finding that the sea floor is a source of low-abundance elements in the ocean up-ends conventional views of marine biogeochemistry.

In the oceans, a near-ceaseless cascade of particles — most of which are produced by biological processes — sinks from the sunlit surface into the darkness of the abyss. This process, known as the ocean's biological pump, transfers chemical energy and the elements required by life to the deep ocean, helping to control Earth's climate and fuelling deep-sea ecosystems[1]. Writing in *Nature*, Du *et al.*[2] effectively flip this view of the ocean upside down by reporting a biogeochemical framework in which multiple elements in the ocean are sourced from the sea floor.

The particulate matter sinking constantly from the ocean surface is often described using precipitation analogies: it consists of a 'rain' of the soft- and hard-tissue carcasses of microscopic algae; and of 'snow' composed of larger, fluffier aggregates of organic and inorganic particles. This literally top-down process successfully explains the oceanic distributions of carbon, nitrogen, silicon and phosphorus — the 'macronutrient' elements needed in large quantities to support marine life. These macronutrients are highly soluble and have ocean-residence times longer than the 1,000-year timescale of global ocean circulation.

However, the distributions of rare 'trace' elements in the ocean are of great interest, too. Bioactive trace elements, such as iron, zinc and cobalt, are also required by life and, alongside macronutrients, strongly affect marine productivity (the amount of organic matter produced in the oceans) and ecosystem structure. The distributions of macronutrients and trace elements are crucial for understanding marine ecosystems[3,4] — arguably as important as temperature and precipitation rates are for understanding terrestrial biomes.

Trace elements that have relatively short ocean-residence times (hundreds of years or less) behave like powdered creamer in a poorly mixed cup of coffee: they tend to be enriched in the ocean near their sources, so that their distributions are generally influenced more strongly by local inputs and removal processes than are those of macronutrients. The distributions of many biologically and scientifically relevant trace elements, including those investigated by Du *et al.*, have therefore eluded concise explanations that rely on top-down mechanisms alone.

Investigations into trace-element distributions and processes in the past few decades have spawned many exciting discoveries and proposed biogeochemical mechanisms. Among these are selective removal of trace elements by specific particle types[5,6]; processes involving complex interactions of trace elements with organic molecules[7,8]; inputs from hydrothermal vents and sea-floor sediments[9,10]; lateral transport of trace elements from continental margins[9] (the zones of ocean floor that mark the transition between continental and oceanic crust); and deposition of elements from the atmosphere[11,12].

Du and colleagues now provide evidence that bottom-up processes also influence the ocean distribution of trace elements. The authors focus on several elements that have relatively short residence times, including neodymium and other rare-earth elements. They measured quantities of these elements in the deep, abyssal Pacific Ocean (depths below 5,000 metres), sampling the seawater above sea-floor sediments, pore water (seawater trapped between sediment grains) and the sediment particles themselves. The measurements suggest that abyssal pore waters provide subtle fluxes of these elements to the ocean. These fluxes make a key contribution to the ocean's biogeochemistry when scaled across the Pacific Ocean's enormous breadth and bathymetry (the 3D shape of the sea bed), on the basis of scientists' current understanding of how waters mix in the deep ocean.

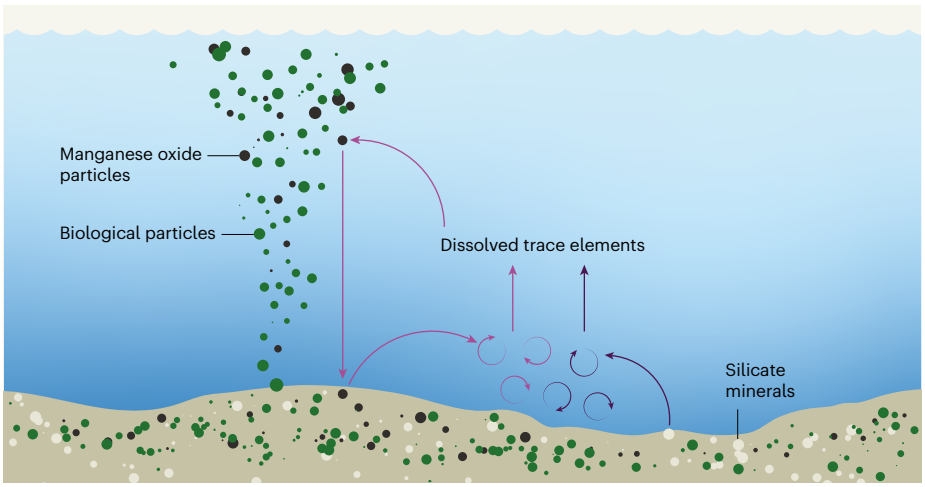

Figure 1 | Cycling of trace elements in the Pacific Ocean. A near-constant flow of particles cascades from the ocean surface to the sea floor. Most are produced by biological processes, but some are inorganic. In conventional top-down models of ocean biogeochemistry, particles reversibly take up some elements from the water column as they sink. Du *et al.*[2] report that manganese oxide particles irreversibly accumulate neodymium, rare-earth elements and probably many other trace elements, so that particle transport to the sea floor is a net sink for these elements. The authors' models suggest that breakdown of organic matter in deep-sea sediments drives chemical changes that generate a source flux of trace elements to the deep ocean; this flux can mix with water at the sea floor before returning to the water column. However, the concurrent breakdown of local silicate minerals in sediments provides a further, previously unknown flux of neodymium to the deep ocean. The findings call for a re-evaluation of marine biogeochemical cycles.

Using highly precise global data from ocean-basin-scale surveys of particulate and dissolved trace elements collected by the international GEOTRACES programme[13,14], Du *et al.* show that manganese oxides (a minor inorganic component of the ocean's particle rain) have a high affinity for neodymium. The authors conclude that sinking manganese oxide particles therefore slowly and irreversibly accumulate neodymium — and probably many other rare-earth elements — from the ocean's water column and carry it back to the sea floor. Consistent with this idea, the authors observed that neodymium and rare-earth elements are predominantly trapped in these inorganic manganese oxides in several sediment types.

The breakdown of organic matter in deep-sea sediments drives slow chemical changes that result in the persistent release of trace elements from sediments back to the deep ocean. Du *et al.* use a combination of numerical models to show that, in addition to the flux of 'recycled' neodymium released in that way, Pacific sediments must also release minor amounts of 'new' neodymium from seafloor weathering of local silicate minerals to account for the isotope distributions mapped out by GEOTRACES. These results have implications for how other trace elements that have a relatively short residence time in the ocean — such as iron, a crucial nutrient — are distributed in the global oceans. The findings also suggest that estimations of the scale of silicate weathering, a process that affects climate over timescales of millions of years[15], need to reconsider the scale of contributions from deep-ocean sedimentary processes.

Measurements of trace elements and rare-earth elements in pore water and sediments are remarkably challenging to collect and are therefore few and far between, which limits opportunities to compare Du and colleagues' results with data from other ocean settings, and to validate the findings. Moreover, the Pacific is more quiescent than other oceans — a feature that benefited the present study, but that makes it hard to know how relevant the findings are to other regions.

Relatedly, it remains difficult to gauge the relative contributions of abyssal sedimentary inputs, top-down processes and sources such as continental margins to other trace-element distributions, and in other regions. On the basis of their models, Du *et al.* argue that differences in the chemistry of abyssal and margin sediments explain the abyssal fluxes proposed in their study. Future revisions to theories of global trace-element distributions and the proposed abyssal sediment sources will undoubtedly require other settings, and suites of trace elements and isotopes, to be considered.

Nevertheless, the picture that emerges from Du and colleagues' analysis is much more 'bottom-up' for many trace elements than is widely recognized. Ocean sediments might even be the dominant input of trace elements for vast swathes of the ocean interior. The proposed flux of trace elements from sediments consists of a component that has been recycled from the abyss, along with a fresh input that is released by weathering of local minerals (Fig. 1). The combined flux diffuses and mixes into the ocean interior, where it is slowly but persistently re-removed from the water column by the rain of particles from the surface.

Importantly, therefore, the authors provide a testable framework for assessing the scale of the involved processes for many other elements, including bioactive ones such as copper, cobalt, nickel and iron. Further measurements of the fluxes invoked by the authors, of the composition of ocean particles and of the affinities of various trace elements will help to determine which, and to what extent, other elements follow this biogeochemical rule set.

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