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Hydrothermal Stamp on the Oceans

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of zircon production during a geologic interval, avoiding spatiotemporal biases linked to variable exhumation and erosion histories that commonly mask more ancient mountain-building events[5]. There has also been a shift to more statistically grounded approaches to address sampling biases. The end result is that detrital zircon records have become established as one of the main tools that we can use to trace the tectonic pulse of the Earth[5]. Despite these advances, many of the zircon peaks identified by Campbell and Allen[1] still stand out in the zircon record. The researchers linked these peaks to the general process of mountain building and supercontinent assembly, but an emerging and more balanced view is probably that peaks in zircon abundance primarily track the production of new granitic crust that largely forms in continental arcs tied to subduction zones[5]. Importantly, mountains can persist well after arc volcanism wanes, as is the case in several modern mountain chains.

Palaeoredox proxy work has also substantially improved over the past decade. Several new proxies that track marine and atmospheric oxygen levels have been developed and the size of palaeoproxy datasets has increased dramatically. With these improvements, our understanding of the structure of Earth's oxygenation has shifted considerably. Rather than a progressive rise to higher oxygenation levels, similar to that discussed by Campbell and Allen[1], an increasingly popular view is one of Earth's oxygenation as a rollercoaster ride, with large swings in atmospheric O_2 levels[6]. Furthermore, mounting evidence suggests that there were jumps to high atmospheric oxygen levels roughly 2.2 to 2.1 billion years ago, as well as about 850 to 800 million years ago[6,7]. These transient increases are marked most conspicuously by the appearance of massive sulfate deposits, a direct reflection of a more oxidizing ocean[7]. Sulfate accumulates and eventually becomes buried as massive evaporates in a well-oxidized ocean–atmosphere system in which pyrite burial is inhibited.

These two more recently identified intervals of oxygenation correspond with lulls in zircon production (Fig. 1) — the opposite of the trend predicted by Campbell and Allen[1] — and presumably periods of limited arc volcanism[5,8]. However, this does not mean that there is a total decoupling between mountain building and surface oxygen levels. Following continent–continent collisions, on-going convergence and crustal thickening will lead to sustained intervals of high topography and high rates of erosion and sedimentation, as observed in the Himalayas today[5]. Additionally, a decrease in volcanism should cause a drop in the amount of reductants being transported from Earth's interior to the surface. Therefore, the tail end (rather than the peak) of significant pulses in orogenic activity could trigger oxidation events. High sedimentation rates favour increased organic carbon burial, which, coupled with reduced volcanic outgassing of oxygen-consuming compounds, could lead to a spike in surface oxygen levels. Building from this framework, tectonically driven perturbations could have been sufficient to destabilize the Earth from the low-oxygen steady state that appears to have characterized most of Earth's middle history[6].

It is difficult to gauge whether these tectonic and atmospheric ties are robust, or whether they will be overturned as proxy records continue to be revised and expanded. There is currently intense debate concerning Proterozoic atmospheric oxygen levels[6,9,10]. Nonetheless, few would disagree that we now have a more realistic and refined view of the history of Earth's oxygenation than we did a decade ago. Similarly, although links between atmospheric and tectonic processes are becoming less tenuous, a clear consensus has not yet emerged.

There is, however, agreement that it is a worthwhile endeavour to attempt to disentangle the respective roles that biotic and tectonic evolution played in shaping the history of Earth's atmosphere — and the work of Campbell and Allen[1] played an important role in developing that line of investigation. ❒

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ANNIVERSARY RETROSPECTIVE

Hydrothermal stamp on the oceans

The composition of the oceans is altered by hydrothermal circulation. These chemical factories sustain microbial life, which in turn alters the chemistry of the fluids that enter the ocean. A decade of research details this complex interchange.

Susan Q. Lang

Shortly after the first discovery of seafloor hydrothermal vents, one of the pioneering researchers described the characterization of additional systems as 'stamp collecting'[1]. Hydrothermal circulation was seen as the reaction between two relatively uniform materials, hot ocean crust and seawater, and so the range of possible geochemical outcomes seemed limited. Hydrothermal chemistry was thought to be controlled primarily by inorganic reactions[1] and of modest importance for ocean chemistry. The past decade has upended these views. Writing in *Nature Geoscience* in 2010, Tagliabue and coworkers[2] demonstrated that Southern Ocean iron concentrations could only be replicated if the input from hydrothermal circulation

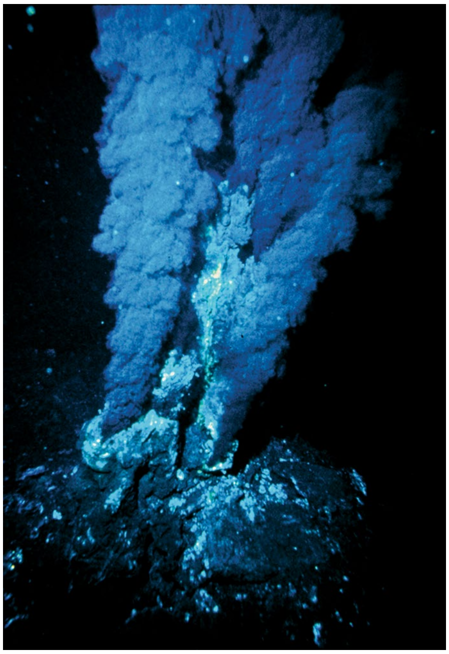

Fig. 1 | A mid-ocean ridge hydrothermal vent from the Atlantic Ocean. Hydrothermal fluids were considered only locally important but Tagliabue and colleagues[2] showed that hydrothermal contributions were necessary to match observed iron concentrations in the world's oceans. As important sources of geochemical energy, studies such as Wankel and colleagues[3] demonstrated that this input to the ocean could also be dramatically altered by microbial interactions with some 50% of hydrogen removed by microbial oxidation. Credit: World History Archive / Alamy Stock Photo

was included, and in 2011 Wankel and coworkers[3] showed that microbial activity can influence hydrothermal fluxes to the deep ocean.

Many of the trace metals that are discharged into the deep sea from hydrothermal vents had been seen as only locally important. They were not believed to contribute significantly to the global make-up of the oceans due to rapid local precipitation (Fig. 1). However, some hydrothermal iron escapes precipitation and is transported far from vent sites[4,5]. In addition, concentrations of dissolved iron across entire ocean basins correlate with those of the hydrothermal tracer ^{3}He (ref. [6]), further suggesting that vents have an influence on ocean chemistry further afield than thought.

Upwelling transports this deep hydrothermal source of iron to the surface where iron availability controls primary productivity. This delivery from the deep increases primary productivity in the surface ocean and impacts the global carbon cycle over millennial timescales. Tagliabue and colleagues[2] used a compilation of dissolved Fe and ^{3}He ratios and a global ocean model to assess the hydrothermal impact on the dissolved iron in the world's oceans. They found the response to the hydrothermal input greatest in the Southern Ocean. Here, the hydrothermal input of dissolved iron contributes at least 5–15% of total Southern Ocean carbon exports.

The global importance of the hydrothermal iron flux has since been widely confirmed. Dissolved hydrothermal iron has been detected in every ocean basin[7], sometimes more than 4,000 km away from the source[8]. Inorganic pyrite nanoparticles — small enough to stay suspended in the water column[9] — and close complexation with organic matter[5,9,10] allow metal transport away from spreading centres.

Acknowledgement of a potential role for organic-iron complexation highlights a second significant shift in thinking about hydrothermal circulation: it emphasizes the importance of microorganisms in mediating the chemistry of the fluids that exit the seafloor. In the case of iron, organisms that obtain energy via oxidation of inorganic compounds — in a process known as chemolithoautotrophy — may provide the organic matter that helps to stabilize and enable its long-distance transport[5]. Therefore, these fluids are far from being the sterile output of water–rock reactions. Instead, they show the unmistakable imprint of biological activity. Beyond iron, microorganisms also alter the volatile and carbon content of hydrothermal fluids resulting in compositions that can be unravelled to reveal subsurface reactions

A notable example of the impact of biological activity comes from Wankel and co-workers[3], writing in *Nature Geoscience* in 2011. Making in-situ flow-rate and volatile measurements, they compared fluids from focused, high-temperature vents — that are so hot as to preclude life — with nearby diffuse fluids that have been conductively cooled and mixed with seawater. Although diffuse fluids had been known to host microbial communities[11,12], in this study they were able to quantify that hydrogen from diffuse vents was 50–80% lower than predicted. This loss of hydrogen was attributed to microbial consumption and biological oxidation. Although similar non-conservative behaviour of biologically reactive chemical species had been shown previously[13,14], Wankel and colleagues were able to demonstrate that the biological impact on hydrothermal venting was quantitatively important to total fluxes into the oceans.

The complexity of these systems is not only in the microbial interactions. Fully integrating the geochemical fluxes associated with hydrothermal circulation into ocean and global elemental cycles has proved difficult because of their heterogeneity in space and time. Early studies showed that episodic events such as fresh magma injections or seismic activity could actually deliver a year's worth of geochemicals to the ocean in the space of a few months[15,16]; systems where seawater circulates through serpentinite rocks instead of basalts and gabbros have fluids with vastly different pHs, temperatures, volatile, metal and carbon content[17]; and the majority of hydrothermal circulation occurs in older crust, far from the ridge axis, and at lower temperatures that result in fluids that are less drastically altered from seawater signatures[18]. Chemical signatures and microbial activity will reflect changes in rock type, temperature and extent of mixing with deep seawater but, so far, much of this variability remains unconstrained. No individual vent field is representative of all hydrothermal circulation, and no single cruise can capture the temporal variability of an individual vent field.

The challenges of characterizing spatial and temporal variability and the biogeochemical interactions of hydrothermal circulation are being addressed on multiple fronts. The continued development of new in situ chemical sensors holds the promise of capturing the temporal variability of individual systems, particularly when linked to cabled observatories that return data continuously and in real time[19]. Devices that incubate microbial cultures at in situ temperatures and pressures may allow better information on the growth rates and metabolisms that alter geochemical fluxes. And the signatures of chemical species in hydrothermal fluids that have received less attention so far — such as organic carbon, nitrogen and phosphorous — will provide additional insights into fundamental relationships.

Ultimately, determining how mass and energy are transferred from the mantle to the deep ocean will require a mechanistic understanding of the interactions between water, rocks and microbes. Recognizing and characterizing the temporal and spatial variations in hydrothermal systems is both critical to understanding ocean chemistry and a feasible ambition. ❐

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ANNIVERSARY RETROSPECTIVE

Slow warming and the ocean see-saw

The slowdown in surface warming in the early twenty-first century has been traced to strengthening of the Pacific trade winds. The search for the causes identifies a planetary-scale see-saw of atmosphere and ocean between the Atlantic and Pacific basins.

Yu Kosaka

Global mean surface temperatures increased less rapidly between the late 1990s and the early 2010s than in the preceding two decades, despite comparable rates of increase in atmospheric greenhouse gas concentrations[1]. This decadal slowdown of surface warming has raised a host of scientific questions. For example, it underlines the need to update our records of aerosol concentrations and of solar irradiance in order to quantify the influence of fluctuations in radiative forcing on Earth's temperature[2]. The distribution of heat in the ocean has been invoked in order to reconcile the slow global surface warming with an increasing greenhouse effect[3]. Regional climate events such as droughts in the southwestern US[4] and the supertyphoon Haiyan[5] are investigated in relation to the global warming slowdown. In terms of the cause of this warming slowdown, natural climate variability in the tropical Pacific Ocean on decadal scales has been identified as a key ingredient. In addition, writing in *Nature Climate Change* in 2014, McGregor and colleagues[6] proposed that an inter-basin see-saw of atmosphere and ocean between the Atlantic and Pacific oceans also contributed significantly.

Modelling studies have attributed the warming slowdown to a mode of decadal climate variability inherent in the tropical Pacific that describes the variability of sea surface temperatures in the Pacific Ocean on timescales of several decades, called the Interdecadal Pacific Oscillation[7]. A negative trend of the Interdecadal Pacific Oscillation features decadal intensification of the Pacific trade winds — that is, prevailing westward surface winds over the tropical Pacific — and surface cooling in the tropical eastern Pacific. Such a pattern of change tends to reduce the global mean surface temperature by cooling the global atmosphere, and thereby counteracts the warming trend that would otherwise occur in response to radiative forcing due to increasing atmospheric greenhouse gas concentrations[8,9].

However, atmospheric and oceanic conditions in the tropical Pacific are coupled and positively feed back on each other. Stronger trade winds promote upwelling of cool subsurface seawater in the eastern equatorial Pacific while pushing sun-baked warm surface water westward. The resultant east–west contrast of sea surface temperature accelerates the trade winds. Because of this feedback, it is difficult to discern causes and effects of phase transitions in the Interdecadal Pacific Oscillation from observed data alone.

McGregor et al.[6] therefore performed a suite of numerical experiments that allowed them to investigate an external trigger that set the feedback in motion. They noted that Atlantic warming since the 1990s can potentially trigger transitions in the phase of the Interdecadal Pacific Oscillation from positive to negative. Tropical atmospheric uplift is facilitated by warmer ocean surfaces, and similarly, downward motion is induced over cool waters. The tropical Atlantic warming and eastern Pacific cooling have therefore been changing the pattern of the Walker circulation, a planetary-scale overturning circulation of the tropical atmosphere that extends in the east–west direction. The trade winds at the surface of the Pacific Ocean are part of the Walker circulation, and they affect the heat exchange between ocean and atmosphere. An intensification of the trades therefore further cools the tropical eastern Pacific and leads to an excitation of the negative phase of the Interdecadal Pacific Oscillation[6,10].

It is thus the inter-basin thermal contrast between the tropical Atlantic and Pacific oceans — rather than solely the Atlantic warming — that drives the circulation changes and initiates an inter-basin see-saw (Fig. 1a). However, ocean–atmosphere interactions in McGregor and colleagues' simulations are limited to thermodynamic effects, and are missing feedbacks in the dynamics. Follow-up studies have shown that allowing the ocean currents to interact with the atmosphere further amplifies the Pacific anomalies in sea surface temperatures and trade-wind strength[10]. Indeed, swings of this multidecadal inter-basin see-saw are found throughout the twentieth century[11] (Fig. 1b).

Moreover, it turns out that the discovery of this Atlantic–Pacific inter-basin see-saw by McGregor and colleagues could help to extend predictability of tropical Pacific climate. Seasonal prediction skill in the tropical Pacific arises from El Niño–Southern Oscillation and has been generally limited to a year, the lifetime of a typical El Niño or La Niña event. By contrast, the predictability