News & views

Climate science

Glacier-sparked volcanism harmed ocean health

Weiqi Yao & Ulrich G. Wortmann

Sediment records from Alaska, spanning the past 20,000 years, suggest that melting glaciers triggered volcanic episodes that removed oxygen in the northeastern Pacific Ocean, explaining 'dead zones' that lasted millennia. **See p.74**

Photosynthesis converts carbon dioxide into organic matter, generating oxygen as a by-product. The reverse process, in which organic matter decays (remineralizes), consumes oxygen and releases CO_2. Rapid mixing and intricate biogeochemical feedback mechanisms stabilize the concentration of oxygen in the atmosphere, but marine oxygen levels vary markedly between regions[1] – with dire consequences for ocean-dwelling organisms that rely on oxygen to live. On page 74, Du *et al.*[2] suggest that the melting of a huge ice sheet several thousand years ago triggered a cascade of events that removed all the oxygen from the intermediate-depth waters of the northeastern Pacific Ocean.

The variability of marine oxygen levels can be understood by dividing the ocean into three zones. Light penetrates the 100–200 metres of water closest to the surface, where wind-induced turbulence, photosynthesis and gas exchange with the atmosphere sustain high oxygen concentrations. Photosynthesis also generates new organic material, resulting in a constant rain of organic matter that is exported to the underlying zone of the intermediate waters. The sinking organic matter decays, thus consuming oxygen in the surrounding waters.

However, unlike the surface waters, the intermediate waters have not been in contact with the atmosphere for decades, and, as a result, oxygen levels fall. The oxygen concentration in this 'oxygen minimum zone' (around 200–1,000 metres below sea level) is therefore strongly affected by changes in the delivery rate of organic matter relative to how fast the intermediate waters are replaced. Because almost all the sinking organic matter decays before reaching the underlying deep waters, oxygen concentrations are higher there than they are in the intermediate waters.

Although oxygen minimum zones are widespread in today's oceans, the complete loss of oxygen is rarely observed. However, during the last deglacial warming (19,000–9,000 years ago), the northeastern Pacific Ocean hosted large, oxygen-free dead zones. Du *et al.* suggest that the development of these dead zones could have been driven by volcanoes that were triggered by the retreat of the Cordilleran Ice Sheet, which covered parts of North America during the Last Glacial Maximum (around 20,000 years ago).

The Cordilleran Ice Sheet reached a thickness of approximately two kilometres, similar to the ice sheet that covers Greenland (Fig. 1). The weight of such large ice sheets can cause the underlying crustal rocks to sink deeper into the mantle, often to the point that the surface of the land is below sea level. When the ice sheet starts to melt, the crust rises again, and the subsequent reorganization of stress and pressure in the rocks can trigger volcanic eruptions[3]. The resulting ash layers decrease the reflectivity of the remaining ice fields and thus absorb more solar radiation. This, in turn, accelerates the melting, increasing volcanic activity further.

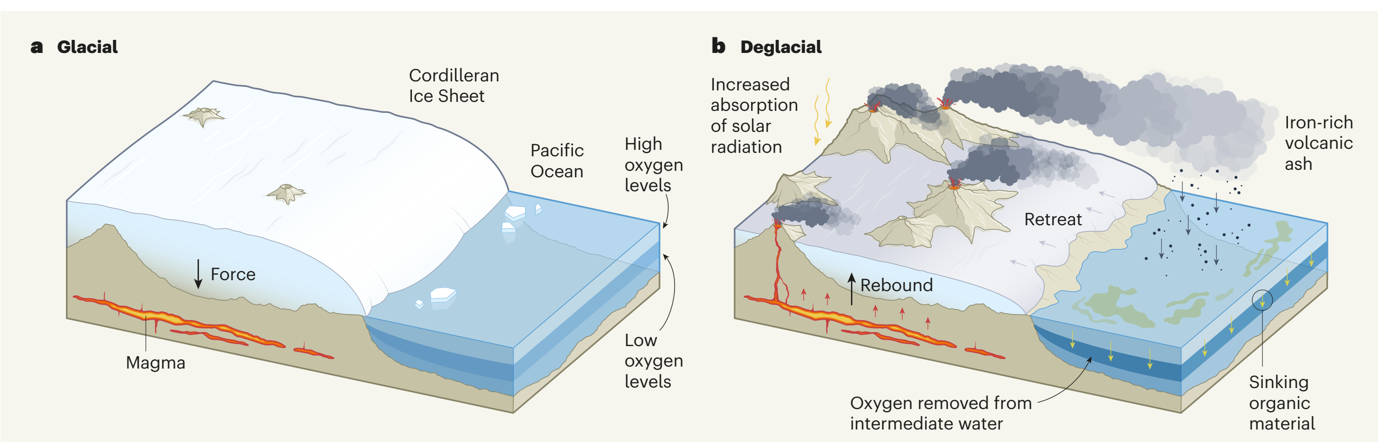

Figure 1 | Deoxygenation through increased volcanism triggered by melting glaciers. a, The weight of the Cordilleran Ice Sheet, which covered parts of North America during past glacial periods, caused the underlying rocks to sink deeper into the mantle. **b**, When the ice sheet began to retreat, the reorganization of stress and pressure in the rocks triggered volcanic eruptions. This released ash that accelerated melting by boosting the absorption of solar radiation, and thus increased volcanism even further. Du and colleagues' study[2] suggests that this process produced enough iron-rich ash to act as a fertilizer, accelerating the production of organic matter in the northeastern Pacific. The authors argue that the sinking organic matter consumed most of the small amount of oxygen that was previously found in the northeastern Pacific waters at intermediate depths, resulting in 'dead zones' that remained inhospitable to complex life forms for millennia. (Adapted from Fig. 4b of ref. 2.)

The northeastern Pacific Ocean provides the perfect example of this feedback mechanism, because it lies adjacent to the seismically active belt known as the 'ring of fire' and contains large amounts of ice. Du *et al.* hypothesized that the iron-rich ash resulting from the increased volcanism acted as a fertilizer — supercharging the production of organic matter in the surface waters, which, in turn, exhausted all the oxygen in the underlying intermediate waters when it was remineralized.

Conceptually, the authors' idea is straightforward. But, as is often the case in geosciences, even simple ideas are difficult to prove, because high-resolution chronologies are hard to obtain. In this respect, Du and colleagues' study is an exception: through a combination of dating approaches, the authors constructed a precise timescale, spanning the past 20,000 years, for sediment samples that they acquired from two sites in the Gulf of Alaska. These data show that the melting of the Cordilleran Ice Sheet coincided with volcanic phases that occurred at the same time as periods of complete oxygen loss in the northeastern Pacific intermediate waters. Although correlation does not equal causation, the authors' idea provides an elegant explanation for the data.

The link between ice-sheet retreat, volcanism and regional ocean deoxygenation is compelling; however, its global relevance remains unclear. Future research will need to look for similar correlations in other places and at different times. Crucially, however, Du and colleagues' work implies that short periods of iron fertilization can lead to long-lasting oxygen deficiencies in marine ecosystems. This is a key observation in the emerging discussion of how global warming will reduce the oxygen content of the ocean, and suggests that, once waters are entirely devoid of dissolved oxygen, the resulting marine dead zones could affect fisheries for millennia. As a corollary, the authors' findings highlight the potential side effects of large-scale geoengineering ideas, such as the use of iron fertilization to increase the amount of organic matter that sinks from the surface and thus boost carbon sequestration to reduce atmospheric CO_2 concentrations[4].

Our planet is currently experiencing unprecedented challenges as a result of global warming. During the past 50 years alone, the total area of oxygen minimum zones has increased fourfold (see go.nature.com/3fqmazr), and ocean models predict that this trend will continue. Although there is some uncertainty as to how much warming we will see in the near future, geological data suggest that oxygen-free waters might become widespread in a warming world[5]. The loss of oxygen from the ocean affects the world's most-extensive and least-explored ecosystems, with unknown consequences for food security[6]. Du and colleagues' work therefore points to the urgent need for improved understanding of how biogeochemical feedbacks affect the health of oceans across the globe.

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Palaeontology

An exceptional fossil lizard from the Jurassic period

Arnau Bolet

Lizards and snakes belong to the highly successful group of reptiles called squamates, but a poor fossil record has obscured their early evolutionary history. A discovery now sheds light on this enigmatic portion of the tree of life. **See p.99**

Our collective imagination tends to picture a palaeontologist as an intrepid character similar to the fictional explorer Indiana Jones, searching for ancient material in remote places. But what comes after specimen gathering is frequently ignored. Tałanda *et al.*[1] show on page 99 that finding a fossil is just the start of the journey. Their discovery, a block of rock exposing a few delicate bones on its surface, was hiding a surprise that only modern imaging techniques could reveal. The sample contained an almost complete skeleton of a tiny lizard, with most of its bones in contact in their original anatomical position (partially articulated). The findings could help to answer questions about the first steps in the evolution of squamates, a group of reptiles that includes lizards and snakes.

The history of Tałanda and colleagues' finding starts with the description in 1998 of the first identified specimens of this lizard, called *Bellairsia,* at a site in Kirtlington, UK, and dated to around 167 million years ago[2]. These specimens belong to one of the oldest known fossil assemblages of lizards, but the fragmentary and disarticulated bones prevented recognition of *Bellairsia* as having a form similar to that of ancestral early squamates. Years later, newly uncovered lizard fossils of a similar geological age, including the block studied by Tałanda and colleagues, were found on the Isle of Skye, UK.

After their discovery, some specimens must undergo lengthy mechanical preparation in the laboratory to be properly exposed for study. Occasionally, however, the bones are too small or too delicate to be prepared mechanically, and an imaging method called computed tomography (CT) is instead used to generate 3D digital models that can be studied without harming the fossils. Although CT has long been used in palaeontology, scanning small specimens requires special instrumentation to achieve high-resolution imaging. Tałanda *et al.* used a combination of high-resolution X-ray micro-CT and phase-contrast synchrotron X-ray micro-CT to generate 3D models of all of the elements contained in the block, including those hidden beneath the surface.

By a great stroke of luck, the unveiled complete skeleton was a mind-blowing finding when compared with squamate fossils of a similar age. But the authors were not done yet with their discoveries. This fossil, identified as the most complete and only articulated specimen of the enigmatic lizard *Bellairsia* found so far, enabled the authors to investigate the animal's evolutionary relationships to other reptiles for the first time, using an approach called phylogenetic morphological analysis. But before they could begin this assessment, Tałanda *et al.* had to check a pre-assembled list of hundreds of morphological characters describing features of bones that would serve as input data for their analyses.

Squamates are astonishingly diverse, with thousands of species adapted to a large array of environments. However, little is known about the initial stages in the evolution of this group, and fossils that record the transition