

develop, gas and volatiles are trapped within the pyroclast. As the interior of the pyroclast cools more slowly, residual volatiles — mainly water — diffuse into growing bubbles and the exterior rind can fracture and crack, causing the clast that was initially formed fluidly to disintegrate brittly. This process could repeat several times while in the fountain, generating progressively smaller fragments by sequential brittle fragmentation. Secondary fragmentation has been reported previously at Piton de la Fournaise<sup>17</sup>, but is now explained in a quantitative theoretical framework.

Taddeucci and colleagues examine the internal textures of pyroclasts from a range of mafic volcanoes and eruptive styles. They find in situ, brittly broken crystals surrounded by intact glass. Using high-temperature laboratory experiments, Taddeucci and colleagues explain the isolated broken crystals by early brittle fragmentation in the shallow conduit, in response to rapid transient deformation, followed by healing of melt fractures through viscous flow. This challenges, but does not exclude, previous interpretations that attribute broken crystals to flow shear or impact breakage<sup>18,19</sup>. The fractures associated with this cryptic brittle fragmentation provide additional surface area for volatile diffusion out of the magma as well as efficient pathways that promote gas migration and outgassing, which affects the development of permeability and thus explosive potential. In addition, Taddeucci and colleagues highlight that unhealed fractures provide planes of weakness vulnerable to later re-breaking, which may further amplify the secondary brittle fragmentation modelled by Namiki and colleagues.

Both of these studies pose challenges for our current methods of hazard assessment. The brittle behaviour observed by Namiki and colleagues was only seen during periods of high gas content within the fountain. As previous studies have identified a link between fountain height (a function of gas content) and the dispersal of fine-grained bubbly pyroclasts<sup>12</sup>, this observed coupling of fragmentation mode and fountain gas content implies that the size distribution, and dispersal, of pyroclasts is dynamic and may even fluctuate during a single fountaining episode. And, if the fracture healing as described by Taddeucci and colleagues is indeed pervasive, then the size distribution of erupted pyroclasts — long taken as an indicator of the energy consumed by fragmentation<sup>16</sup> — may not reflect the true fragmentation efficiency.

We still have some way to go before we can claim a fully quantitative understanding of the range of conditions under which these two mechanisms operate. To forecast the expected particle size distribution for mafic eruptions based on specific eruptive parameters requires further integrated field, experimental and modelling studies. These must account explicitly for the rheological properties of multiphase magmas (melt + bubbles + crystals), which are at present poorly constrained compared to more simplified single- and two-phase scenarios.

Namiki et al. and Taddeucci et al. add fuel to the debate over the role of brittle fragmentation in mafic explosive eruptions. For accurate assessment of volcanic hazards associated with explosive mafic eruptions further mechanistic and quantitative understanding of brittle fragmentation in low-viscosity magmas is needed, but these two studies suggest that not only

are the conditions for fracturing met more commonly than previously thought, sequential fragmentation may also be the norm. □

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#### Competing interests

The author declares no competing interests.



## OCEAN BIOGEOCHEMISTRY

# Shunt or shuttle

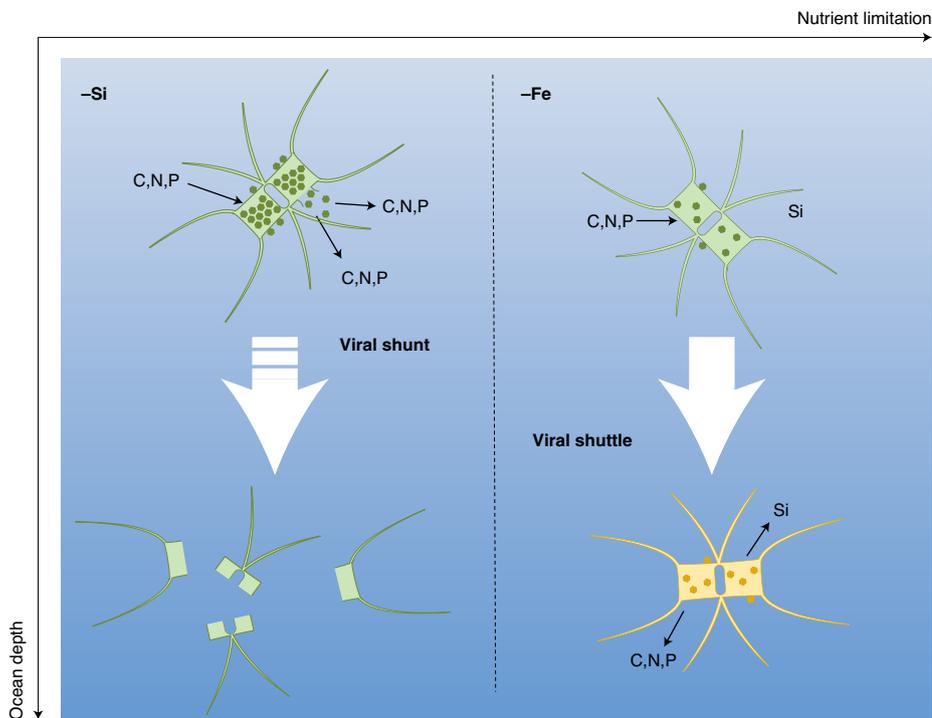
Nutrient availability influences the susceptibility of marine primary producers to viral infection. For diatoms in iron-limited waters, reduced infection rates impact marine biogeochemical cycles by enhancing the flux of material to depth.

Alex J. Poulton

**V**iruses are ubiquitous on Earth. Some viruses cause severe diseases in humans, but others can play crucial roles in our environment. In the ocean, viruses are the most abundant lifeform —

around  $10^{23}$  viral infections occur every second<sup>1</sup>. Oceanic viruses help to recycle material, bursting cells open to release essential nutrients back into the seawater and making them available again for marine

microbes, killing 25 to 50% of the newly generated marine microbial biomass each day<sup>1</sup>. They can be preferential as to who they infect, and organisms can exhibit varied susceptibility to their infection. Writing in



**Fig. 1 | Fate of carbon and nutrients (nitrogen and phosphorus) fixed by infected diatoms.** Heavy viral load and rapid cell lysis in silica-limited waters leads to recycling of carbon and nutrients in the upper ocean (the viral shunt), with only diatom detritus lost to depth<sup>7</sup>. In iron-limited waters, as shown by Kranzler and colleagues<sup>2</sup>, low viral loads and slow lysis rates result in the sinking of whole diatom cells to the deep ocean (the viral shuttle), carrying their carbon and nutrients to depth.

*Nature Geoscience*, Kranzler and colleagues<sup>2</sup> show that a key group of photosynthetic marine protists, diatoms, are less susceptible to viral infection and suffer slower deaths when starved of the essential nutrient iron. The delayed mortality of diatoms from viral infection may enhance the flux of material into the deep sea, and the sequestration of carbon dioxide in the ocean.

Diatoms contribute a fifth of total primary production on Earth. They sustain marine ecosystems, take up carbon dioxide from the atmosphere via photosynthesis and contribute to the transfer of this fixed carbon from the upper ocean to the deep sea<sup>3,4</sup>. A unique characteristic of diatoms is their opaque siliceous cell walls, which are known as frustules. These elegant glass-like structures not only provide surprising levels of protection from being crushed and eaten by marine grazers<sup>5</sup>, but also offer extra ballast for material to sink into the deep ocean<sup>4</sup>.

Silica is essential for diatoms. Its availability in the ocean controls their growth and survival, while the availability of other nutrients such as nitrogen and phosphorus are also tightly linked to

ocean productivity. The availability of these essential nutrients limits diatom productivity across much of the ocean<sup>6</sup>. Other elements, however, are also required for growth, at much smaller relative concentrations. In remote areas of the oceans, for example, iron is a major limiting nutrient. This leaves a complex pattern of nutrient-limitation across the surface ocean, in which diatoms are either nutrient replete or severely limited by a lack of nitrogen, silica, phosphorus or iron<sup>6</sup>.

Sampling across this mosaic of nutrient-replete and nutrient-limited regions, including the California coast and sub-Arctic Pacific, Kranzler and colleagues use metatranscriptomics to characterize diatom–virus associations, observing lower levels of viral infection and reduced viral replication in iron-limited waters. To explore these field observations further, they grew bloom-forming diatoms in the laboratory under iron-replete and iron-limited conditions and infected them with diatom viruses. In these experiments, iron-limited diatoms exhibited delayed mortality and the viruses present showed reduced replication compared to the replete ones. Based on

the combination of field and laboratory results, the authors conclude that diatoms partly escape viral lysis in iron-limited conditions, leading to much lower levels of virus replication, extracellular viruses, and delayed death of the diatoms.

It is surprising that iron-starved diatoms show higher resilience to viral infection, especially in light of recent work<sup>7</sup> identifying enhanced susceptibility to infection when silica is limiting their growth. The results of these two studies suggest that limitation by different nutrients may have contrasting influences on diatom population dynamics. This in turn can lead to different fates of their cellular material and the carbon they fix during photosynthesis (Fig. 1).

How diatoms die dictates where their cellular material ends up in the ocean. Their biomass can either be recycled in the surface when their cells break down or neatly packaged into faecal pellets or marine snow on a fast-ride to the deep ocean. Viral infection of diatoms can lead to either of these fates, depending on how susceptible diatoms are to viral infection and how that infection progresses. Kranzler and colleagues have now identified that the limiting nutrient is a key determinant of their susceptibility and fate.

In silica-limited conditions, viruses shunt cellular material from particles into the dissolved phase after lysing cells and liberating essential nutrients, leading to the retention and recycling of fixed carbon and nutrients in the upper ocean<sup>1</sup>. In iron-limited conditions, however, diatom viral infection is impaired, and cell lysis is delayed. The slowed viral infection, in this case, turns out to enhance the loss of diatoms to the deep sea, enhancing the sequestration of their fixed carbon (and other nutrients) into the deep ocean<sup>2</sup>.

In addition to limitation by one element, co-limitation by two elements can also occur at the same time (see, for example, refs. <sup>8,9</sup>), with limitation changing cell properties and ecology. For example, iron-limited diatoms put more silica into their frustules and boost their sinking rates. How co-limitation and limitation by other essential nutrients, for example, nitrate, cobalt or zinc, impact the interactions between viruses and diatoms will be worthwhile avenues for future research. These new insights will further shape our knowledge of the role that diatoms play in marine biogeochemical cycles.

Kranzler and colleagues provide valuable insights into the dynamic interaction between diatoms and viruses in nutrient-limited oceanic regions. This interaction controls the growth and death of marine diatoms and dictates the fate of

diatom carbon, silica and other elements in the ocean. □

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## ENVIRONMENTAL IMPACTS

# A world view of pesticides

Pesticide pollution is a widespread issue. A global risk assessment of 92 active pesticide ingredients suggests 2.5 billion hectares of agricultural land are at risk of pollution by more than one active ingredient.

Rupert Lloyd Hough

When Rachel Carson wrote *Silent Spring*<sup>1</sup> in 1962, our knowledge of pesticides was relatively limited. The book that ignited America's environmental movement provides a series of examples and case studies about the damage to ecosystems and humans that synthetic pesticides can bring. Yet, at the time, systematic analyses of environmental impacts of pesticides were lacking. Sixty years on, such analyses remain limited, although research on the impacts of specific pesticides on human health and the environment now has more depth and mechanistic rigour. We still lack the global picture needed to establish a mandate for global pesticides reduction and answer questions like, what is the magnitude of impacts globally, and where in the world do pesticides pose the largest risk? Writing in *Nature Geoscience*, Tang et al.<sup>2</sup> provide the first major attempt to plug this critical gap, identifying South Africa, China, India, Australia and Argentina as regions of highest concern because high pesticide pollution, high biodiversity and high water scarcity all intersect.

Pesticides have adverse impacts on water quality, plants and animals, and are associated with an abundance of negative human health effects, from short-term sickness to numerous cancers. However, reduction in their use is not easy. Intensive agriculture is reliant on pesticides to maintain yields (Fig. 1). The systematic breeding-out of diversity and drive for simplified production systems has left crops vulnerable to pests and diseases. The recent European Union ban on neonicotinoid seed-dressings is a case in point, which leaves many farmers unable to grow a successful oil seed rape crop<sup>3</sup>. Without



**Fig. 1** Pesticide pollution poses widespread risks to water resources and ecosystem diversity globally. Credit: Dusan Kostic / Alamy Stock Photo

new disruptive thinking on crop production, global pesticide usage is likely to increase, with knock-on effects on the environment and our health.

Previous studies into environmental fate, transportation and risks posed by pesticides are dominated by site-specific investigations. A small number have taken a more extensive viewpoint to evaluate regional or global impacts<sup>4–7</sup>; nevertheless, they are limited to a specific class of pesticide or a specific environmental resource, such as surface water.

Tang et al. significantly extend this picture by providing a global analysis of the 92 most applied active ingredients

in agrichemicals. By evaluating their risks to water sources, biodiversity and agricultural lands, they build the first ever global atlas of pesticide risk. Results suggest that 64% of global agricultural land (about 2.5 billion hectares) is at some risk of pesticide pollution by more than one active ingredient. More importantly, 34% of high-pollution-risk areas are in high-biodiversity regions and 5% in water-stressed environments.

Tang and co-authors evaluate the potential risk of pesticide pollution across global agricultural land based on the level of hazard it may pose to local ecosystems and environments. They split the globe into