modern setting with an oxygen-rich atmosphere, as the oxygen tends to oxidize any reduced phosphorus.

Pasek and Block show that natural lightning strikes can indeed reduce phosphate to a lower oxidation level[2]. They collected fulgurite glasses, which are produced from cloud-to-ground lightning strikes, from a variety of locations. Fulgurites consist of a glassy core of melted and subsequently solidified material, which records the lightning's path through the ground, surrounded by a rough outer surface of unaltered grains of sand and soil. They can form in a variety of settings: Pasek and Block examined samples from quartz sands, clay soils and calcic soils.

Using a microprobe and nuclear magnetic resonance spectroscopy to determine the state of the phosphorus incorporated into the fulgurites, they found ample evidence for the existence of reduced phosphorus in the form of phosphite and hypophosphite. The amount of reduced phosphorus available in each sample was dependent on the soil conditions where the fulgurites had been found, but the results clearly indicate that lightning-driven reduction of phosphate occurs, even in the presence of an oxygenated atmosphere. Furthermore, the degree of reduction detected in these objects was substantial: in one fulgurite 68% of the original phosphate was reduced to soluble phosphite.

These results indicate that relatively high concentrations of reduced phosphorus could be leached from the fulgurites by groundwater, and thus become locally available to organisms. Although the impact of this process would be minimal on a global scale, it could be an important effect in providing increased amounts of an essential nutrient locally, particularly in areas with frequent lightning strikes.

More than 50 years ago, it was proposed that phosphite and hypophosphite might have been readily synthesized (and used) under the reducing, low-oxygen atmosphere of early Earth[7]. This suggestion has largely been discredited, as the early atmosphere is no longer thought to have been strongly reducing. But it now seems that other reducing conditions, such as the transient environment created by lightning strikes, may be sufficient to trigger this transformation.

Pasek and Block[2] show that reduced phosphorus species are produced by natural processes today, albeit in small amounts. This finding provides a rationale for the continued existence of an otherwise superfluous metabolic pathway in modern terrestrial microbes, allowing the microbes to use rare, reduced species of phosphorus if they were available, rather than competing for phosphate. ❐

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VOLCANISM

Eruptions and extinctions

Fossils from southern China provide evidence for a mass extinction during middle Permian time, 260 million years ago. The close association of this event with an outpouring of lava, initially into the sea, indicates that explosive volcanism may have been the cause.

Nicholas Christie-Blick

During middle Permian time, southern China experienced a massive, short-lived burst of volcanic activity[1,2]. The scattered remnants of the resulting Emeishan large igneous province, which are today spread over an area of hundreds of thousands of square kilometres, attest to the scale of volcanism. During the early stages of this event, lava and sea water interacted explosively, at least in some parts of the province, forming thick accumulations of fragmental material[2]. Around the same time, more than half of extant marine invertebrate genera became extinct[3]. In a recent *Science* paper, Wignall and colleagues contend that the two events may be related, with the copious release of noxious gases having a role in triggering a biotic crisis[4].

Extinction is the ultimate fate of all species — very likely including our own. An intriguing feature of the past 550 million years of Earth history is that the intensity with which organisms disappeared is remarkably uneven: five great mass extinctions[5] have been recorded, and a dozen or so lesser events. Figuring out what caused these mass extinctions has attracted a great deal of scientific interest. The deleterious effects of both extraterrestrial impacts and the voluminous outpouring of lava have been invoked, but no single mechanism has been universally accepted[6].

Establishing that a particular volcanic episode led to a mass extinction requires precise constraints on the relative timing of volcanic activity and the disappearance of organisms. This is not easy because the sedimentary rocks bearing fossil evidence for extinction commonly crop out far from the volcanic rocks invoked as a cause. Southern China is unusual in that respect: fossil-bearing marine limestones and the volcanic rocks of the Emeishan large igneous province can be studied in the same outcrop sections. This setting is therefore favourable for investigating the temporal relationship between volcanism and mass extinction.

Wignall and colleagues studied several sections within the Emeishan region that span the middle Permian[4]. The lower parts of these sections are dominated by fossil-rich limestones that are interpreted as having been deposited in a marine setting. These beds are overlain by volcanic rocks interstratified with fossil-bearing limestone. From one of the key sections, at Xiong Jia Chang, the researchers record an abrupt change in rock type and fossil taxa that together imply a marked, if brief, deepening of the depositional environment. This contact, between foraminifer- and algae-bearing limestone and radiolarian chert, corresponds with the level of the mass extinction, according to the researchers. The close proximity of the

Figure 1 | Explosions in the middle Permian. The light-coloured material resulted from explosive lava–water interaction during the Emeishan volcanic episode and was deposited on top of a lava flow (dark). Wignall and colleagues suggest that such eruptions could have pumped substantial quantities of noxious gases into the atmosphere, causing severe environmental effects[4].

oldest volcanic rocks of the Emeishan lava pile, which lie between one and two metres above this interval, leads Wignall and colleagues to infer a close temporal relation between volcanism and extinction.

The researchers contend that the enormous scale of volcanism associated with the Emeishan province would have pumped substantial quantities of sulphur dioxide (a noxious gas) into the atmosphere. Moreover, the aerosols formed during this episode would have stopped some sunlight from reaching the Earth, thereby cooling the planet and further stressing the environment. Such cooling has been recorded in the case of more recent eruptions such as the 1815 explosion of Tambora in Indonesia[7].

The oldest volcanic rocks documented by Wignall and colleagues in the Xiong Jia Chang section consist of fragmental material caused by explosive interactions between the hot lava and sea water. Their data support earlier evidence for the widespread occurrence of such deposits in the Emeishan province[2]. These explosive eruptions would have packed a substantially stronger punch than just lava, suggest the researchers, because the fragmentation process would have increased the efficiency of the release of harmful gases. It has been estimated that the original (pre-erosional) volume of the Emeishan volcanic rocks was on the order of half a million cubic kilometres[1]. Precise radiometric ages are not available but palaeomagnetic constraints indicate that much of the volcanic activity occurred within the geologically brief interval of about one million years[1]. Emeishan volcanism thus seems to have been capable of causing severe environmental perturbations.

A key issue with the interpretation of Wignall and colleagues is the confidence with which extinction and volcanism can be correlated. The geological relations that they report from the Xiong Jia Chang section permit volcanic activity to have begun after the middle Permian extinction. It is possible, however, that eruptions began slightly earlier elsewhere in the Emeishan province, or that the global extinction level is a little younger than the horizon recognized at Xiong Jia Chang. It also remains to be determined whether correlation necessarily implies causality.

In an earlier evaluation of the relationship between large igneous provinces and mass extinctions[1], four mass extinction events were tentatively linked to volcanism, though in each case, and at that time, the onset of eruptions seemed to be slightly later than the main phases of extinction. A recent study that thoroughly re-evaluated the temporal relationship between end-Triassic extinction and the Central Atlantic magmatic province concluded that there is no support for the idea that magmatism began before the extinction event[8]. As with the study by Wignall and colleagues, the extinction level and volcanic rocks are preserved in the same sections.

The Emeishan large igneous province is of interest not only for the clues it may hold on mass extinctions. The province has also been regarded as one of the best examples of short-lived, kilometre-scale crustal doming above a mantle plume before the onset of volcanism[9]. But the observational evidence for such uplift has been challenged on the basis of the re-interpretation of some of the geology[2].

Among the stratigraphic observations offered in support of crustal doming are marked thinning of middle Permian carbonate rocks in the vicinity of the Emeishan province, decreasing ages of the carbonates away from the volcanic centre, and evidence for the development of an erosional surface on the carbonates with at least tens of metres of relief[9]. However, these observations may also be explained in other ways. For example, the interplay between tectonic subsidence and deposition of the carbonates can result in a stratigraphic pattern similar to that observed. Although such a pattern may have been modified by minor subaerial erosion, the scale of erosional relief has yet to be clearly documented and differentiated from primary relief arising from physiographic complexities in the carbonate platform.

The findings of Wignall and colleagues[4], as well as the Correspondences on page 530 and 531 of this issue concerning plume-driven doming[10,11], suggest that there is much to be learnt about the Emeishan province in China. Clearly, the region is the key to unravelling more than one intriguing question about the role of volcanism in Earth history, including the causes of mass extinctions and the role of mantle plumes in the generation of large igneous provinces. ❐

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