EVOLUTION

Plants escaped an ancient mass extinction

A global biodiversity crash 251.9 million years ago has revealed how ecosystems respond to extreme perturbation. The finding that terrestrial ecosystems were less affected than marine ones is unexpected.

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Changes in Earth's biodiversity recorded in fossils over various spatial and timescales reveal the comings and goings of species as they emerge and go extinct, and offer insights into how both species and the ecosystems they inhabit respond to perturbation. These patterns of the past provide models that might help us to understand the changes that life on Earth will experience in the future. The end-Permian mass extinction, often called the mother of mass extinctions[1], is a focus of such studies. Large waves of extinctions occurred over a time interval of 60,000 to 120,000 years[2] at the end of the Permian period, which lasted from 298.9 million to 251.9 million years ago. Fossil studies indicate that more than 90% of marine invertebrates went extinct[3] as a consequence of extreme perturbations of the conditions on Earth, including intense volcanic activity. Writing in *Nature Communications*, Fielding *et al.*[4] and Nowak *et al.*[5] reveal what happened to terrestrial plants during the end-Permian crisis. Both contributions are well supported by an array of data, and both tell a slightly different story.

How terrestrial ecosystems were affected during the end-Permian mass extinction is not as well understood as the changes that occurred in marine ecosystems. There are biases in the fossil record of plants, and the invertebrate and vertebrate communities they supported, because the preservation potential of these organisms is highly dependent on the physico-chemical conditions of where they lived[6]. Larger plant components, such as leaves or stems (the macrofloral parts), are easily broken down, and this material is often recycled in the ecosystem. By contrast, plant reproductive material — spores and pollen — are protected by molecules that prevent degradation. Spores and pollen are produced annually at logarithmically higher numbers than other plant parts that sit above ground, which favours their preservation in sediments over more easily decayed plant structures.

Moreover, rocks from around the time of the extinction event are notoriously incomplete — sediments from certain times can be missing from ancient rock layers[7]. When this relative incompleteness of rock layers that would preserve fossil parts is added to the equation, interpreting patterns of species presence during this key episode in our planet's history becomes complicated.

Fielding and colleagues report a regional study that uses the plant fossil record of spores, pollen and macrofloral remains in layers of rock from the Sydney Basin, Australia, in which layers from the time of the end-Permian crisis event are reported to be present. The authors present a comprehensive data set that includes an analysis of the layers, fossils and geochemistry within a known time frame. Synthesizing their data, the authors propose that the onset of a short-lived change in summer temperatures and a rise in seasonal temperatures across eastern Australia, about 370,000 years before the onset of the end-Permian marine extinction event, caused the regional collapse of *Glossopteris* flora (Fig. 1). Fossils of this extinct plant are preserved mainly in ancient wetlands, and it was the dominant type of forest species in the Southern Hemisphere. Other Southern Hemisphere records seem to show that *Glossopteris* survived for some time into the subsequent Triassic period (which lasted between 251.9 million and 201.3 million years ago) in Antarctica[8], although exactly when they went extinct in the Triassic is unknown. Fielding and colleagues use the region-specific collapse of *Glossopteris* as a scenario for how vegetation might respond to current global warming. A regional loss in the Southern Hemisphere of a major plant group that has growth requirements highly sensitive to climate change, particularly in the temperature requirements for its essential processes, might be a harbinger of the plant group's ultimate extinction.

Fielding and colleagues' finding that the extinction of *Glossopteris* occurred about 370,000 years before the marine extinction event, and was coincident with the onset of massive volcanic activity, should now lead to investigations elsewhere in the Permian record to determine whether the loss of other wetland plants acts as a 'canary in the coal mine'.

One long-held model[9,10] for terrestrial ecosystem turnover and replacement of

WILD HORIZONS/UIG/GETTY

Figure 1 | Fossilized leaves of *Glossopteris* from Australia. *Glossopteris* flora were a dominant forest species in the Southern Hemisphere in ancient times. Fielding *et al.*[4] and Nowak *et al.*[5] report their analyses of plant fossils, including *Glossopteris*, which reveal that ancient plants from around 251.9 million years ago did not undergo the mass-extinction event that was seen in marine invertebrates at that time.

species between the Permian and the end of the Middle Triassic (between 251.9 million and around 237 million years ago) has focused on the effects of a global trend towards aridification. It was proposed that, after a worldwide collapse of plant communities and a mass extinction of species that cascaded through the food chain[9], there was a change in the floral species across global landscapes by the Middle Triassic period. For the demise of *Glossopteris*, Fielding and colleagues find no evidence of an aridification trend in their region that would suggest that a hot terrestrial landscape promoted a mass extinction of plants during the time of the end-Permian crisis.

This conclusion of Fielding and colleagues' regional work is supported by a comprehensive analysis of plant fossil records on a global scale conducted by Nowak and colleagues. The authors analysed the patterns of previously reported plant fossils from 259.1 million to around 237 million years ago, which spans the end-Permian mass extinction and the Early and Middle Triassic. They generated a database that includes information on more than 7,300 plant macrofossils and nearly 43,000 fossil records of pollen or spores. So far, this is the most comprehensive database generated for floral analysis before and after the end-Permian crisis. It amasses the evidence that has been considered by many palaeontologists to indicate a trend in mass extinction of terrestrial plants that mirrors that of the marine mass extinction[9].

The authors present origination, extinction and turnover patterns at the level of species and genera on a stage-by-stage basis (stages being steps in the geological timescale). The diversity of genera was relatively constant across the time interval, although the species diversity of macrofloral fossils dropped 251.9 million years ago. The diversity of genera represented by spores and pollen remained constant across the time frame studied, although Nowak *et al.* note a small decline in species-level diversity around 251.9 million years ago. Of the groups of plants that have either pollen or spores, the spore-bearing ferns, as well as the pollen-producing seed ferns and cycads, declined in diversity during this time, whereas the pollen-bearing conifers and ginkgos increased in diversity.

In contrast to prevailing wisdom, Nowak and colleagues demonstrate that land plants did not experience widespread extinction during Earth's most severe biological crisis. Their conclusion is similar to that drawn for terrestrial vertebrates[11]. This leaves the relationship between the end-Permian marine mass extinction and the effect on land at the time enigmatic for now, and still up in the air for further investigation. ■

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CONDENSED-MATTER PHYSICS

Materials in flatland twist and shine

Four studies demonstrate the vast opportunities provided by stacking pairs of monolayer materials and changing the resulting optical properties by twisting one material with respect to the other. SEE LETTERS P.66, P.71, P.76 & P.81

BERNHARD URBASZEK & AJIT SRIVASTAVA

Atomically thin materials are currently being investigated for fundamental research and applications in optics and electronics, because they interact strongly with light and have fascinating magnetic properties. When two different monolayer materials are brought into contact to form a bilayer, electrons can no longer move freely in the planes of the atomic layers. Instead, they are trapped in spatially periodic potential-energy variations called moiré potentials, as a result of interactions between the layers[1]. These nanometre-scale potentials are caused by the layers having different orientations or lattice constants — parameters that describe the dimensions of a unit cell in a crystal lattice. Moiré potentials have been predicted to strongly modify the optical properties of such bilayers[2]. Four papers in this issue[3–6] report observations of optical emission and absorption that confirm this prediction.

Monolayers of materials called transition-metal dichalcogenides (TMDs) have strong in-plane covalent bonds, and can therefore be produced by exfoliation (the removal of sheets from a bulk crystal) in a similar way to graphene — a single layer of carbon atoms. However, unlike graphene, atomically thin TMD crystals are semiconductors that have an energy gap between their higher-energy (conduction) and lower-energy (valence) electronic bands. Consequently, charge carriers in these materials that are excited by light or that are injected using a voltage can relax from the conduction band to the valence band by emitting particles of light (photons).

Just as the weak attraction between layers lends itself to exfoliation, it also allows two monolayers of different TMDs (such as tungsten disulfide and molybdenum diselenide) to be stacked on top of each other to form what is known as an artificial heterobilayer (Fig. 1a). If the layers are periodic crystals that have slightly different lattice constants, the electronic properties of each layer are modified by the presence of the other layer. Specifically, the electronic states and band structure of the heterobilayer depend on the spacing and relative alignment of the atoms.

Because of the slight mismatch in the lattice constants of the two layers, arrangements of atoms in the heterobilayer change periodically: atoms of metals (such as molybdenum and tungsten) are positioned on top of each other at certain points, whereas atoms of chalcogens (such as sulfur and selenium) are aligned at other points. These different configurations of atoms, known as registries, result in different energies for the valence and conduction bands, as verified by scanning tunnelling microscopy[1]. Consequently, electrons in the plane of the heterobilayer are subject to periodically changing bands, and, if the variations in the band energies are sufficiently large, electrons are trapped in moiré potentials.

An attractive feature of such heterobilayers is the tunability of their periodic potential. Adding a slight twist during the stacking process, or exchanging one lattice with another that has a different lattice constant, leads to moiré potentials that have a different spatial periodicity. This feature enables the electronic properties of layered materials to be tailored in a fundamentally new way. As a result, heterobilayers are becoming a playground for exploring exotic quantum phenomena — rather like how the strong interactions between electrons in twisted bilayers of graphene have led to the spectacular observation of superconductivity in electronic-transport studies[7].

The four current papers investigate the impact of moiré potentials on light emission