Magazine section: **Features**

Wipeout

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A major catastrophe 251 million years ago left life teetering on the brink of oblivion. Now for the first time we have a clear picture of what caused it, says leading palaeontologist Michael Benton

251 MILLION years ago, at the end of the Permian period, life on Earth was almost completely wiped out by an environmental catastrophe of a magnitude never seen before or since. All over the world complex ecosystems were destroyed. In the sea, coral reefs, fishes, shellfish, trilobites, plankton, and many other groups disappeared. On land, the sabre-toothed gorgonopsian reptiles and their rhinoceros-sized prey, the dinocephalians and pareiasaurs, were wiped out forever. Only 5 per cent of species survived the catastrophe, and for the next 500,000 years life itself teetered on the brink of oblivion. What terrible event could have wrought such havoc?

Two theories have been proposed - the impact of a huge meteorite or comet over 10 kilometres in diameter, or a massive and prolonged volcanic eruption. Up to now the evidence has been equivocal. But the data has been accumulating over the past 10 years, and the picture is now clear enough to say with some certainty what happened.

An impact might seem a tempting model. A massive catastrophe demands an extraordinary explanation - something unexpected, something from outer space. And we know that impacts can cause mass extinctions. It seems that the dinosaurs and many other groups of animals and plants were wiped out 65 million years ago by the impact of a huge meteorite in modern day Mexico. The crater has been found, there is good evidence for the shock wave, and for the fallout rocks and dust all round the world.

In February 2001, a team of scientists claimed they had found clear evidence that the mass extinction at the end of the Permian was also caused by a meteorite impact. Luanne Becker of the University of Washington in Seattle and her colleagues from NASA and other institutions announced in a paper in *Science* (vol 291, p 1530) that they had found extraterrestrial helium and argon in rocks from the Permo-Triassic boundary in China and Japan.

The gases were trapped inside the fullerenes or buckyballs that are often associated with impact debris. When Becker and her team looked closely at the helium and argon they found isotope ratios like nothing else on Earth, but similar to those found in meteorites. On this basis they argued that the fullerenes - and their entrapped gases - must have come from an impact.

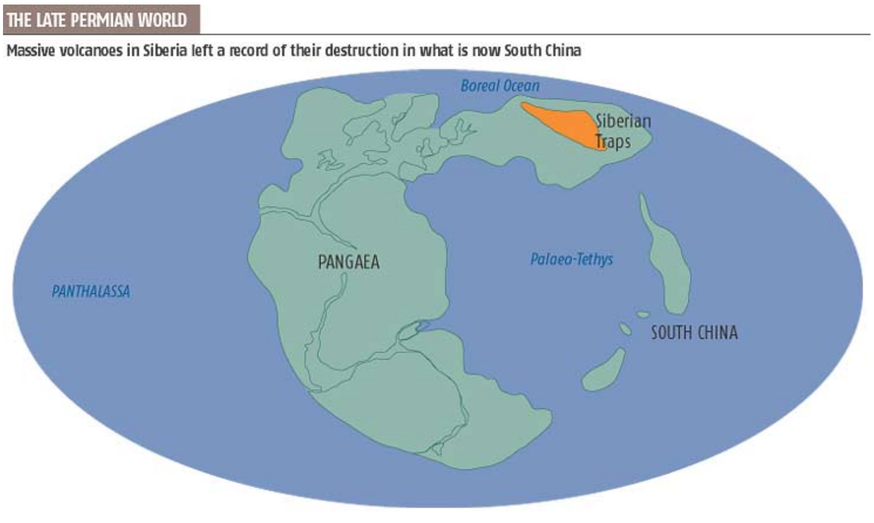
The claim was splashed all over the press. On 23 February 2001, *The New York Times* reported "Meteor crash led to extinctions in era before dinosaurs". *The Times* said, "Asteroid collision left the world almost lifeless".

But later in 2001, several learned journals published critiques in which other geochemists tried and failed to replicate Becker's results. Other samples from the same boundary bed in China apparently contained no buckyballs, argon or helium, and a Japanese geologist, Yukio Isozaki of the University of Tokyo, pointed out that the Japanese sample came from a rock formation that didn't even include the Permian-Triassic boundary.

But Becker and her team still stand by their results. They repeated their analyses from the Chinese samples, and confirmed the helium result. They also have support from an independent source. In September 2001, Kunio Kaiho of Tohoku University in Japan reported that sediment grains from Permo-Triassic boundary sections in China show evidence of compression by impact, as well as geochemical shifts indicative of a huge impact - though his data is far from conclusive.

All in all, the evidence for an impact at the Permo-Triassic boundary is limited when compared with the mass of evidence for an asteroid hit at the end of the Cretaceous: the iridium anomaly (a worldwide spike in the abundance of iridium, an element derived from meteorite impacts); shocked quartz (grains showing evidence of high-pressure modification); glassy spherules (melt particles derived from sedimentary rocks); and above all an enormous crater of the correct age. The discovery of a Permian equivalent of any of these could confirm the impact theory at any moment. But for now, most geologists do not accept the impact model for the crisis at the end of the Permian.

Instead, their attention has focused on Earth-bound processes. The idea is that massive volcanic eruptions, sustained over half-a-million years or more, caused catastrophic environmental deterioration - poison gas, global warming, stripping of soils and plants from the landscape, eruption of gases from their frozen locations deep in the oceans, and mass deoxygenation. The evidence for this version of events is compelling compared with the impact hypothesis.

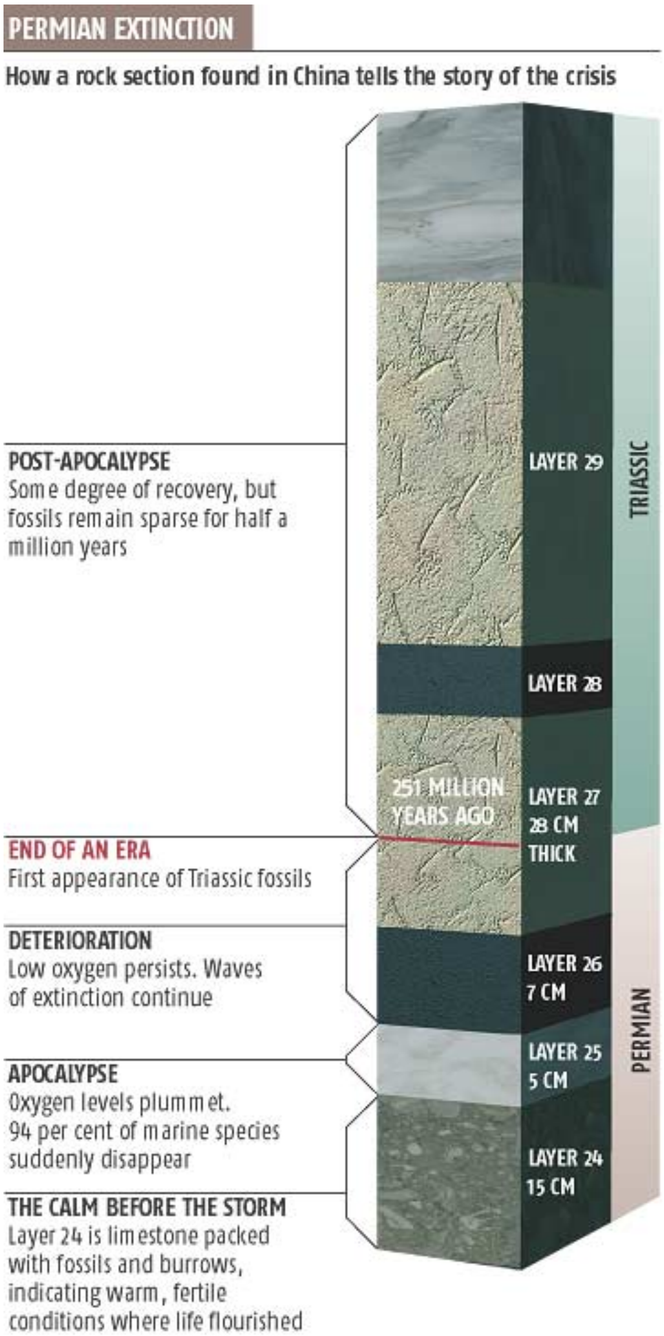


First and foremost, the end of the Permian was indeed characterised by huge volcanic eruptions. The remains of these are preserved in the Siberian Traps, a vast accumulation of basalt lavas some 3 million cubic kilometres in volume and covering 3.9 million square kilometres of what is now eastern Russia. Precise dating of the Siberian Traps shows that they span the boundary between the Permian and the Triassic, with the eruptions beginning perhaps 500,000 years before.

The Siberian Traps were not formed by explosive eruptions from classic cone-shaped volcanoes. More commonly, basalt is erupted through fissures, long cracks in the ground, as happens on Iceland today. Such eruptions last for a long time, and the lava bubbles up in huge volumes, spreading sideways from the fissure. They are accompanied by prodigious outpourings of gases, mostly carbon dioxide.

The effect of these gases was devastating. The full story of the havoc they wrought is written in the sedimentary rocks that span the Permo-Triassic boundary. Until the 1990s, geologists had to rely on incomplete or hard-to-date sections in northern Italy, Pakistan and Afghanistan. Reputedly excellent sections in southern China were not available to overseas geologists, mainly for political reasons.

Nothing daunted, British geologists Tony Hallam of the University of Birmingham and Paul Wignall of the University of Leeds obtained a modest travel grant from the Royal Society, and went to China in 1991. What they found amazed them: the rock record was complete, and it told the story of the crisis millimetre-by-millimetre as they worked their way through the rocks from bottom to top.



Hallam and Wignall focused on sections around the Meishan township. Working up through the succession, the last rocks deposited in the Permian were limestones containing diverse and abundant fossils, such as foraminiferans (microscopic shelled protozoans), brachiopods (lamp shells), and conodonts (jaw elements from primitive fish-like vertebrates). Rarer fossils include cephalopods (coiled molluscs that are distant relatives of the modern squid and octopus), sea urchins, starfish and small crustaceans called ostracods, all typical of warm, shallow seas. Near the top, there is extensive burrowing in the limestones, indicating conditions of full oxygenation. Clearly, life at this time was diverse and abundant.

Then, suddenly, everything changes. The thick, burrowed limestones disappear, and with them the abundant fossils. The limestone is capped by a mineral-rich layer containing lots of pyrite - a classic marker of very low atmospheric oxygen. On top of this are three layers of limestone, mudstone and clay, encompassing about half a million years. These layers, numbered as beds 25, 26 and 27 in the Chinese system, tell how the crisis unfolded, so let's look at them in more detail.

The oldest layer, bed 25, is a thin band of pale-coloured clay 5 centimetres thick in which fossils are very rare, just a few foraminiferans and conodonts. Under the microscope, this clay contains small iron-rich pellets and decayed pieces of quartz that indicate it was formed from an acidic "tuff", an amalgam of volcanic fragments and ash from an explosive volcanic eruption - presumably the Siberian Traps.

The next bed up, number 26, consists of 7 centimetres of dark, organic-rich limey mudstone in which fossils are slightly more abundant - there are brachiopods, clams and cephalopods. Based on the relatively diverse fossils, and on geochemical evidence, oxygen levels during deposition of bed 26 were low but not anoxic.

Together, beds 25 and 26 form a distinctive dark-on-light marker band that has been detected elsewhere in China, which is useful for geologists who wish to make correlations from location to location. This "ash band" has been detected so far in 12 provinces throughout China, covering at least a million square kilometres. Whatever created it was extremely far-reaching.

Bed 27 indicates some degree of environmental recovery. The 17-centimetre-thick layer of limestone is full of burrows, so bottom conditions were not especially low in oxygen. The lower part of the bed contains occasional Permian brachiopod fossils near the base. Near the top, the conodont *Hindeodus parvus* appears for the first time: this is the globally accepted marker for the beginning of the Triassic period. (Geological boundaries are marked by the appearance of fossils, not their disappearance. The major event happened at the base of bed 25, but no significant new species appeared until the middle of bed 27.)

What does it all mean? One of the stories the Meishan section tells is of a dramatic extinction event. In the late 1990s, Jin Yugan and his colleagues from the Nanjing Institute of Geology and Palaeontology, and Doug Erwin from the National Museum of Natural History in Washington DC, undertook a huge sampling programme. They found that at the base of bed 25, 116 marine species suddenly disappeared, representing 94 per cent of the total. Then, in the following 500,000 years stretching to the top of bed 27, new species appear then disappear with alarming speed. Overall a further 45 species dropped out, one at a time. Clearly something terrible happened at the base of bed 25 and its ramifications continued for half a million years.

But what exactly happened? Fortunately, the Meishan rock section, and other sections elsewhere, contain a record of environmental changes through the Permo-Triassic crisis, in the form of isotopes of oxygen and carbon. Both elements have two stable, naturally occurring isotopes whose ratios fluctuate depending on environmental conditions. The isotope ratios are locked into the skeletons of organisms during their lifetimes, so careful recordings from the shells of bivalves or foraminiferans, for example, can give a detailed picture of atmospheric and oceanic conditions through time.

Oxygen isotopes are used as a palaeothermometer. Oxygen occurs in two forms, oxygen-16 and oxygen-18. These are incorporated into the calcite skeletons of marine creatures at different rates depending on the water temperature, more oxygen-18 at low temperatures, and more oxygen-16 at high. At the base of bed 25, the main mass extinction level, there was a sudden shift in the oxygen isotope ratios indicating a worldwide rise in temperature of 6 °C. This may not sound much, but it would have a profound effect on the world's ecology. Climatologists have been getting very excited recently about a half-a-degree rise in global temperatures.

The carbon isotopes suggest what might have caused the temperature increase. They show a massive shift towards the light isotope, carbon-12, exactly at the time of the big extinction. Pulses of carbon-12 in the geological record are usually indicative of a volcanic eruption or a large die-off (plants, animals and bacteria concentrate carbon-12 in their bodies and release it when they die). Both certainly happened at the end of the Permian. But the carbon-12 pulse is far too big to be explained by these mechanisms alone. Calculations of global carbon budgets have suggested that, even if every plant, animal, and microbe died and was buried, altogether they would only account for about one-fifth of the observed carbon shift. The Siberian Traps would have added another fifth. Where did the remaining three-fifths come from?

The extra carbon-12 was probably buried, frozen deep under the oceans in the form of gas hydrates. These are extraordinary accumulations of carbon-12-rich methane locked up in cages of ice at very high pressure. If the atmosphere and oceans warm up sufficiently, these gas reserves can suddenly melt and release their contents in a catastrophic way. The explosion of gas through the surface of the oceans has been termed a "methane burp". A very large methane burp at the end of the Permian could have produced enough carbon-12 to make up the deficit.

The cause of the burp was probably global warming triggered by huge releases of CO_2 from the Siberian Traps. Methane is a greenhouse gas too, so a big burp raises global temperatures even further. Normally, long-term global processes act to bring greenhouse gas levels down. This kind of negative feedback keeps the Earth in equilibrium. But what happens if the release of methane is so huge and fast that normal feedback processes are overwhelmed? Then you have a "runaway greenhouse". This is a positive feedback system: excess carbon in the atmosphere causes warming, the warming triggers the release of more methane from gas hydrates, this in turn causes yet more warming, which leads to the release of more methane and so on. As temperatures rise, species start to go extinct. Plants and plankton die off and oxygen levels plummet. This is what seems to have happened 251 million years ago.

The effects were profound and long-lasting. In the Meishan section, the Permo-Triassic boundary in bed 27 is followed by a succession of dark limestones and shales containing sparse fossils. This seems to represent a post-apocalyptic world, in which CO_2 levels were still very high and the oceans and atmosphere were starved of oxygen. The 6 per cent of species that survived the initial onslaught were struggling. Normal recovery processes had not yet kicked in. When oxygen levels fall, plants and photosynthesising plankton in the sea normally replenish it by absorbing excess CO_2 and generating oxygen. After the crash at the end of the Permian, perhaps oxygen levels had been driven so low, and so much of plant life had been killed, that this was impossible.

The surviving species were a very poor sample of what had lived before: thin-shelled molluscs that required very little food and swam languidly over the black, deoxygenated muds, and the "living fossil" *Lingula* in its shallow burrows. Near the end of the Permian period, each region of the world had its own fauna and flora. Afterwards, the survivors became cosmopolitan. It took 20 or 30 million years for coral reefs to re-establish themselves, and for the forests to regrow. In some settings, it took 50 million years or more for full ecosystem complexity to recover. Geologists and palaeontologists are only just beginning to get to grips with this most profound of crises.

Michael Benton
Michael Benton is head of the Department of Earth Sciences at the University of Bristol. His book on the end-Permian crisis, When Life Nearly Died, has just been published by Thames & Hudson, price £16.95