MASS EXTINCTIONS

MICHAEL J. BENTON

NewScientist

INSTANT EXPERT

9

Woolly rhinos and mammoths died out in an extinction event 11,000 years ago

BOTH ITV/REX FEATURES – BACKGROUND PASCAL BLONDE/GETTY

WHAT IS A MASS EXTINCTION?

Extinction is a normal part of evolution. Species come and go continually – around 99.9 per cent of all those that have ever existed are now extinct. The cause is usually local. For example, a lake might dry up, an island might sink beneath the waves or an invasive species might outcompete another. This normal loss of species through time is known as the background rate of extinction. It is estimated to be around 1 extinction per million species per year, though it varies widely from group to group.

The vast majority of species meet their end in this way. Most dinosaurs did not die out in the asteroid strike – after 165 million years of evolution, hundreds or thousands of species had already been and gone.

Sometimes many species disappear together in a short time. At the end of the ice ages 11,000 years ago, for example, mammoths, woolly rhinos, cave bears and other large mammals adapted to cold conditions died out across Europe and North America. There have been many such "extinction events" through the history of life.

Occasionally extinction events are global in scale, with many species of all ecological types – plants and animals, marine and terrestrial – dying out in a relatively short time all over the world. This is a mass extinction.

There is no exact definition of a mass extinction. The loss of 40 to 50 per cent of species is about the norm, but this is only the upper end of a spectrum of extinction events. There is no set timescale either: some extinctions happen relatively quickly, like the KT event, others take several million years, as in the late Ordovician. It depends on the cause (see page vi).

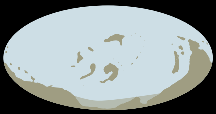
> "Until quite recently, geologists were conditioned against seeing evidence of major crises of any kind"

THE BIG FIVE (OR IS IT SIX, OR SEVEN?)

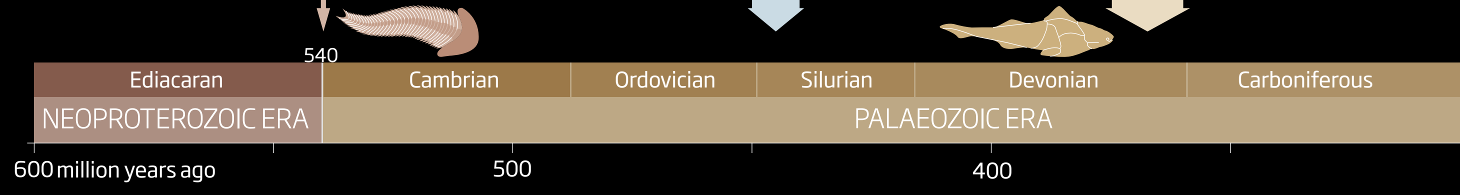
We now recognise that there have been several mass extinctions over the past 600 million years – the period over which macroscopic life has existed in relative abundance. The first of these was about 540 million years ago, at the end of the Neoproterozoic era (see geological timescale, below), when the enigmatic Ediacaran animals disappeared. Some palaeontologists also identify the late Cambrian as another time of mass extinction.

Three further mass extinctions punctuate the Palaeozoic era. The late Ordovician, between 450 and 440 million years ago, saw substantial losses among the dominant animals of the time: trilobites, brachiopods, corals and graptolites. The late Devonian mass extinction, beginning around 375 million years ago, was another long and drawn out affair. Armoured fish known as placoderms and ostracoderms disappeared, and corals, trilobites and brachiopods suffered heavy losses. The Palaeozoic ended with the enormous end-Permian mass extinction (see page v).

Another 50 million years or so passed before the next mass extinction, at the end of the Triassic. Fish, molluscs, brachiopods and other marine groups saw substantial losses, while extinctions on land opened the way for the dinosaurs. They dominated for 135 million years before being wiped out in the most recent extinction, the Cretaceous-Tertiary (KT) event (see page iv).



Extinction	**End-Neoproterozoic**	**Late Ordovician**	**Late Devonian**
Date	540 million years ago	450-440 mya, in two pulses	375-360 mya, possibly in
Cause	Unknown	Glaciation?	Anoxia?
Genera extinct	Unknown	57 per cent	50 per cent
Major groups lost	Ediacarans	None	Armoured fish



DEATH ON A MASSIVE SCALE

Every now and again, life on Earth faces a crisis. At least five times in the past 540 million years half or more of all species have been wiped out in a short space of time. These mass extinctions are important punctuation marks in the history of life, as once-dominant groups are swept away and replaced with new ones. What triggers this wholesale regime change? How does life recover? And are we in the middle of a mass extinction of our own making?

Given how important mass extinctions are to understanding the history of life, it may seem surprising that no one was much interested in the idea until the 1970s. Of course, the great Victorian palaeontologists such as Richard Owen and Thomas Huxley were aware that dinosaurs and other ancient creatures were extinct, but they did not see any role for sudden, dramatic events.

Following Charles Darwin, they argued that extinction was a normal process: species originated at some point by splitting from existing species, and at some point they died out.

This mindset can be traced back to Charles Lyell, who in the 1830s argued that the foundation of sane geology was uniformitarianism. This holds that "the present is the key to the past": all geological phenomena can be explained by processes we see today, extrapolated over enormous periods of time.

In fact, until quite recently, geologists were conditioned against seeing any evidence of major crises. Woe betide anyone who believed in past impacts and explosions, the marks of an unscientific catastrophist! Until the 1950s geologists even denied that the Earth had been hit by meteorites, arguing, for example, that Meteor Crater in Arizona was a volcanic collapse feature.

This all began to change in the 1960s, a time of ferment and revolution for geologists when ideas of an immobile Earth were rejected in favour of the dynamic reality of plate tectonics.

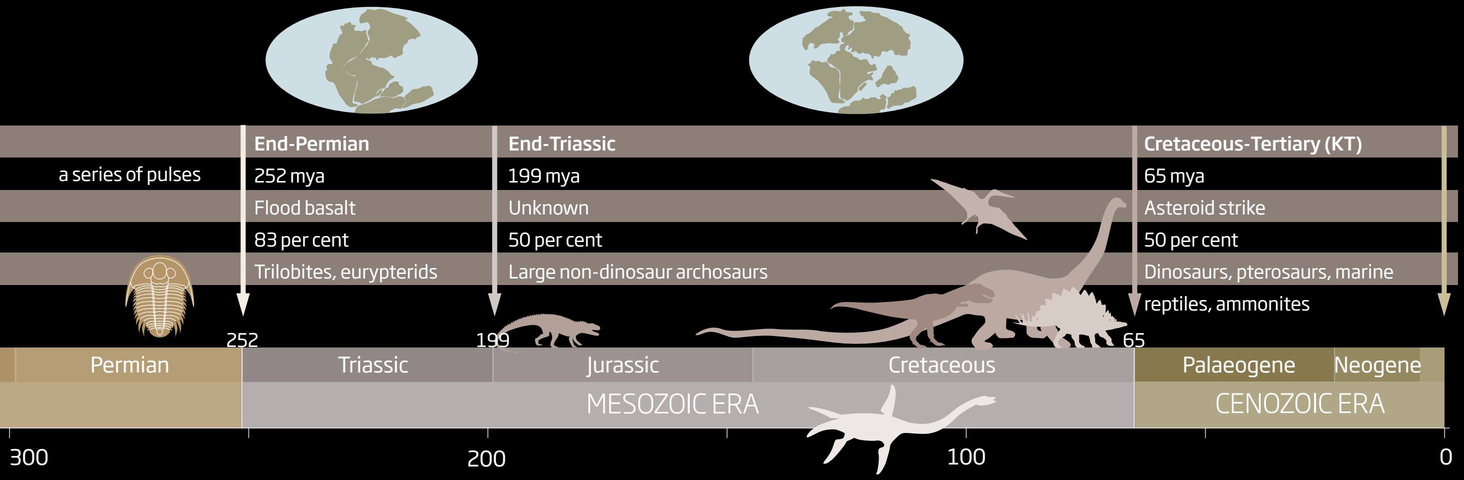
That decade also saw the birth of impact geology. Gene Shoemaker of the California Institute of Technology in Pasadena identified rare minerals, such as coesite and stishovite, in the floor of Meteor Crater, and argued that these were evidence of an impact. At the time such minerals were unknown in nature and had only been created in the lab using enormous temperatures and pressures.

Shoemaker also investigated a large circular depression called Nördlinger Ries in Bavaria, Germany. There he found coesite and stishovite, along with suevite, a type of rock composed of partially melted material. The depression is now considered to be an impact crater some 16 million years old.

Around the same time, palaeontologist Norman Newell of Columbia University in New York began building the case that the fossil record contained evidence of large-scale extinctions. With his work the concept of mass extinctions began to gain currency. Even so, when Luis Alvarez at the University of California, Berkeley, and his colleagues proposed in 1980 that the dinosaurs had been killed off by an asteroid impact the world was still not ready to believe it. Opposition to the idea was substantial, and it took another decade to convince the world that this massive catastrophe really happened.

Arizona's Meteor Crater, the birthplace of impact geology

CHARLES AND JOSETTE LENARS/CORBIS



	End-Permian	**End-Triassic**	**Cretaceous-Tertiary (KT)**
a series of pulses	252 mya	199 mya	65 mya
	Flood basalt	Unknown	Asteroid strike
	83 per cent	50 per cent	50 per cent
	Trilobites, eurypterids	Large non-dinosaur archosaurs	Dinosaurs, pterosaurs, marine reptiles, ammonites

THE DEMISE OF THE DINOSAURS

The extinction of the dinosaurs 65 million years ago, at the Cretaceous-Tertiary (KT) boundary, is the most recent of the major mass extinctions and the one most amenable to study. Rocks from before, during and after the event are more abundant, detailed and datable than those for older events. So its cause was just waiting to be resolved.

Up to the 1970s the best evidence suggested that the dinosaurs – along with pterosaurs, mosasaurs, plesiosaurs, pliosaurs, ammonites and many other groups – declined slowly over some 10 million years as a result of cooling climates.

Then came the bombshell. In 1980 Luis Alvarez, who had already won a Nobel prize in physics, his geologist son Walter and other colleagues published an astounding paper in *Science* (vol 208, p 1095). The team had set out to use the element iridium as a geological timekeeper, but ended up with remarkably different findings.

Iridium is very rare on Earth's surface, and the minute quantities that are present arrived on meteorites. These hit the Earth at a low but steady rate, so iridium can be used to mark the passage of time: the concentration of iridium in a sedimentary rock indicates how long the rock took to form.

The method worked well when the team applied it to thick sections of sedimentary rock on either side of the KT boundary at Gubbio in Italy. But at the boundary itself they found a sharp spike in iridium, 10 times the normal amount. If they had stuck to their original hypothesis, they would have concluded that the rocks were laid down by unusually slow sedimentation over a vast time span. But they rejected that in favour of the idea that the spike indicated a sudden influx of iridium from a very large meteorite or asteroid. This, they argued, was what had caused the mass extinction.

The team reasoned that such an impact would have sent up a vast cloud of dust that encircled the globe, blacking out the sun, preventing photosynthesis and so causing massive loss of life. They calculated that a crater some 100 to 150 kilometres in diameter was required, implying an asteroid 10 kilometres across.

The paper caused an outcry, mainly because it drew such a remarkable conclusion from modest evidence – but such is the stuff of the most daring scientific advances. As the 1980s progressed, geologists found more and more evidence for an impact, including iridium spikes in dozens of locations around the world, the high pressure minerals coesite and stishovite, "shocked" quartz grains, glassy spherules of melted rock and the sudden extinction of many groups of plankton worldwide. Around the Caribbean they also found ancient tsunami debris, and in 1991 the crater itself was identified at Chicxulub on Mexico's Yucatán peninsula (see map, below). As predicted, it was 130 kilometres across.

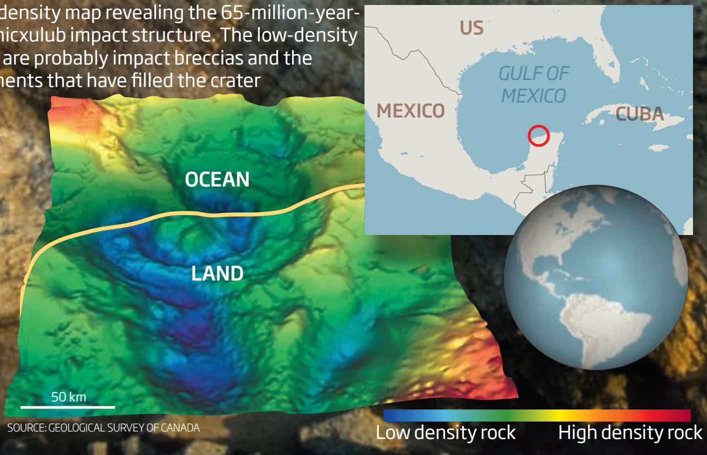
There are still some serious loose ends to tie up, not least the role played by massive volcanic eruptions on the Deccan plateau of India around the time of the extinction. A handful of geogists dispute whether the impact coincides with the extinction. Even so, the consensus now is that the Alvarez team was right.

The skull of *Dinogorgon*, which died 252 million years ago along with most other animals and plants

ROGER RESSMEYER/CORBIS

Luis (left) and Walter Alvarez in 1985 with a sample of the rock that led to their impact theory

A 3D density map revealing the 65-million-year-old Chicxulub impact structure. The low-density rocks are probably impact breccias and the sediments that have filled the crater



SOURCE: GEOLOGICAL SURVEY OF CANADA

THE TERRIBLE TWO

By their very nature extinction events are a big deal, but two really stand out, one for its sheer scale and the other for its sudden, spectacular and shocking cause

WHEN LIFE NEARLY DIED

One mass extinction truly dwarfs all the others. Whereas earlier and later events each seem to have extinguished about 50 per cent of species, the end-Permian extinction was associated with a loss of 80 to 90 per cent of species in the sea and on land. Several major groups disappeared, including trilobites and giant sea scorpions called eurypterids.

The vast scale of the extinction is shown by the fact that two major structural ecosystems disappeared – reefs and forests. Nothing like that has happened in any of the other mass extinctions.

Reefs first appeared in the Cambrian, and by the Permian had become a major ecosystem hosting substantial biodiversity, as they do today. With the loss of the dominant reef-builders, the rugose and tabulate corals, the Earth was cleared entirely of reefs. It took 15 million years for new groups of coral to evolve and build reefs once more.

Forests likewise virtually disappeared. There is a famous "coal gap" in the early and middle Triassic when no forests anywhere became sufficiently established to produce coal deposits. Key groups of forest insects, soil churners and vertebrates disappeared too.

Such a huge devastation of life might seem to imply a colossal impact. Evidence for this, however, is weak to non-existent. The most-favoured explanation is volcanic eruptions: 252 million years ago, massive volcanoes erupted in Siberia and they continued to belch forth viscous basalt lava and massive clouds of gases for 500,000 years. These were not conventional cone-shaped volcanoes but great rifts in the Earth's crust. The rock from the eruptions now forms a vast formation known as the Siberian Traps.

Sulphur dioxide caused flash freezing for a short time by blocking the sun, but this gas dissipated rapidly. More long-lasting was the greenhouse gas carbon dioxide, which caused global warming and ocean stagnation. Repeat eruptions kept pumping carbon dioxide into the atmosphere, perhaps overwhelming the normal feedback in which plants mop up the excess through photosynthesis. The warming probably also released frozen masses of methane, an even more potent greenhouse gas, from the deep oceans.

The earliest Triassic rocks contain evidence of repeat cycles of ocean stagnation: their black colour and rich supply of pyrite indicate oxygen-poor conditions. These dark, sulphurous rocks contain very few fossils, in contrast to the abundant and diverse fossils in the limestones just below the extinction level. On land, the volcanic gases mixed with water to produce acid rain. Trees died and were swept away together with the soils they anchored, denuding the landscape. Land animals perished as their food supplies and habitats disappeared.

The slaughter of life in the sea and on land left a devastated Earth. Pulses of flash warming continued for 5 million years, delaying the recovery of life. Some "disaster taxa" such as *Lystrosaurus*, a pig-sized herbivore, gained a foothold here and there, but it took 10 to 15 million years for complex ecosystems to become re-established.

LIFE REBOUNDS

Mass extinctions are devastating, and yet life eventually returns to normal. The rate of recovery depends on many factors, but the most important is the scale of the extinction.

After most mass extinctions life recovers within a few million years, though the end-Permian event was different. It was twice as large as most of the others, and so it is no surprise that the recovery time was greatest.

Recovery also depends on which plants and animals survive. If the mass extinction hit all groups more or less equally, as most seem to, then there is a good chance that one or two species from each major group will survive. These act as an ecological framework, occupying most of the broad niches, and so the basic ecosystem structure survives. New species evolve to fill the gaps and the recovered ecosystem may be quite comparable to the one that existed before the disaster.

A more selective event, on the other hand, might leave broad sectors of ecospace vacant. A variety of the survivors then jockey for position, evolving to fill the vacant niches.

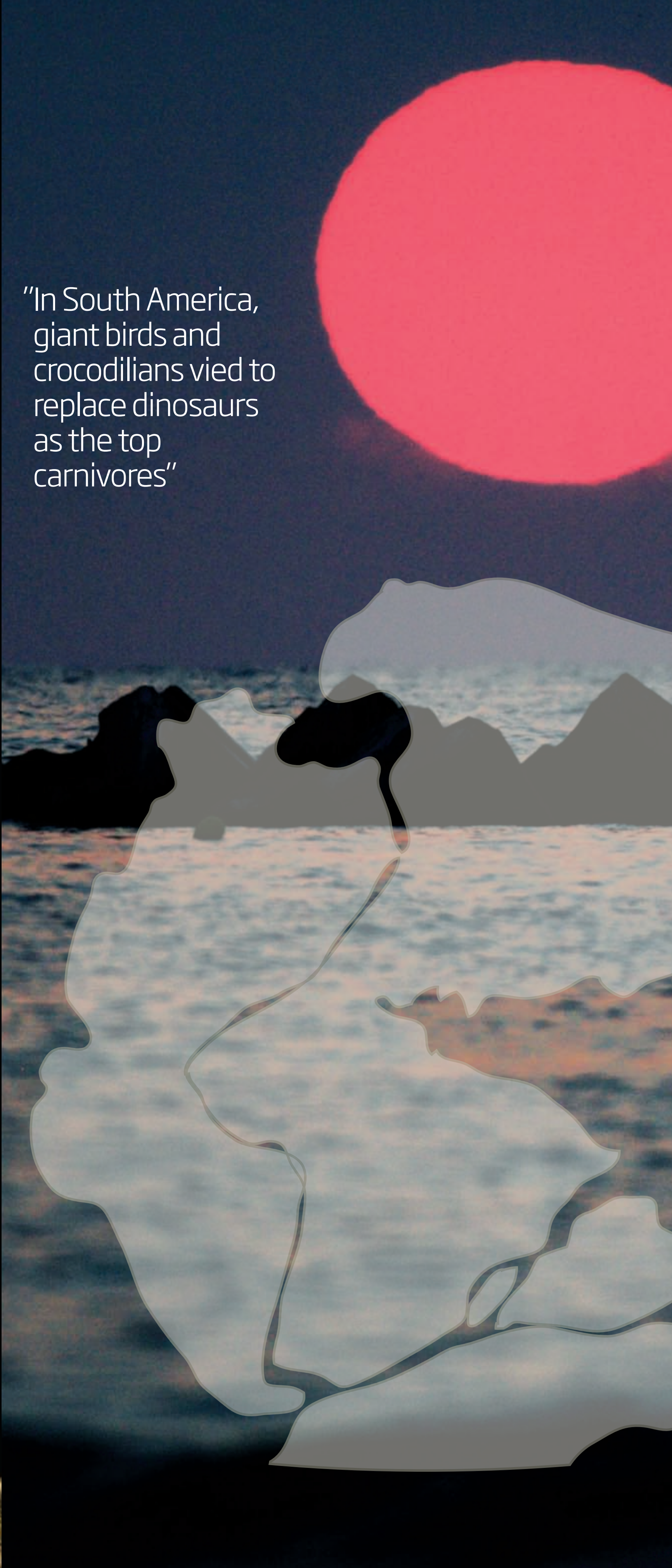
After the KT event it was by no means a foregone conclusion that mammals would take over. Indeed, in North America and Europe, giant flightless birds became the dominant carnivores, some of them famously preying upon ancestral (admittedly terrier-sized) horses. In South America, giant birds and crocodilians vied with each other to become the top carnivores, and mammals only replaced them some 30 million years later.

Mass extinctions, then, have a creative side. Marginal groups sometimes get a chance to expand and become dominant. Most famously, mammals benefited from the demise of the dinosaurs. In fact, mammals first evolved in the late Triassic, at the same time as the dinosaurs, but they remained small and probably nocturnal because dinosaurs occupied all the key niches.

The end-Permian mass extinction was even more creative, with a yawning post-extinction eco-space providing opportunities for the survivors. In the sea, molluscs (bivalves and gastropods) took over roles previously occupied by brachiopods. Scleractinian corals rebuilt the reefs, and new kinds of light-scaled fish moved into roles previously occupied by more primitive ones. On land, the key beneficiaries of the extinction might have been the dinosaurs, whose earliest ancestors emerged within 5 million years of the crisis.

Parts of the post-dinosaur world were briefly ruled by giant birds like *Gastornis* (above), before mammals took over

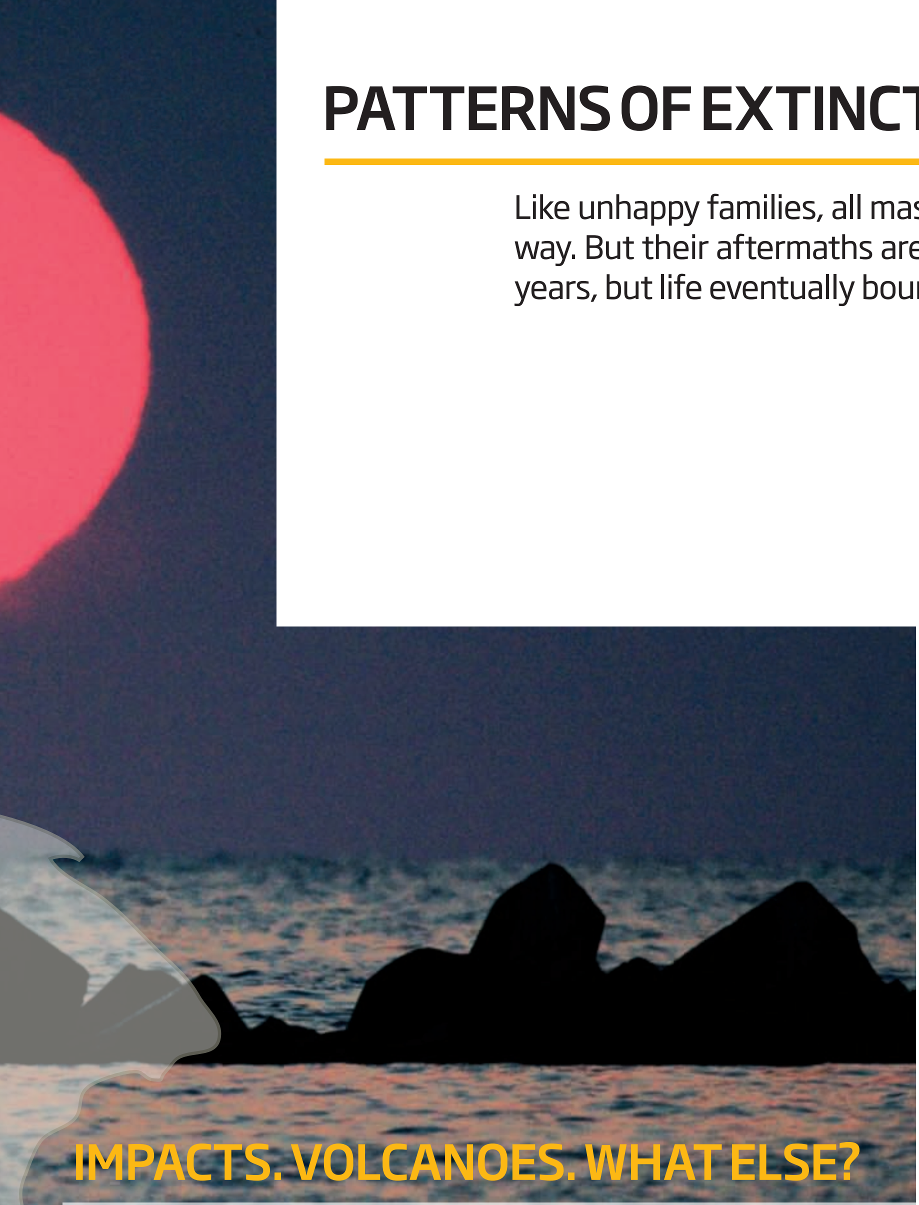
BOTTOM: D.CHAPMAN/WOODFALL WIDE IMAGES/NHPA; BELOW: DE AGOSTINI/GETTY



"In South America, giant birds and crocodilians vied to replace dinosaurs as the top carnivores"

PATTERNS OF EXTINCTION AND RECOVERY

Like unhappy families, all mass extinctions are unhappy in their own way. But their aftermaths are surprisingly similar. It takes millions of years, but life eventually bounces back



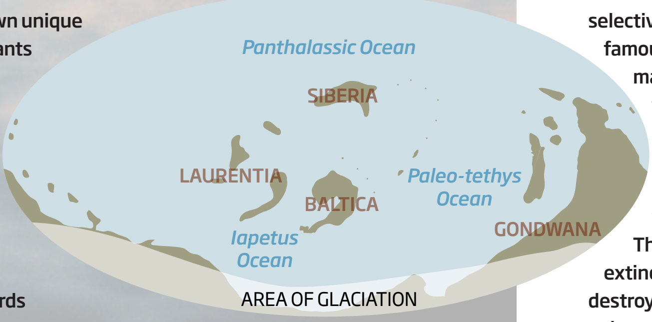
IMPACTS. VOLCANOES. WHAT ELSE?

The causes of two of the largest mass extinctions are now reasonably well understood (see pages iv and v). But what of the others? In some cases it is difficult to say. The fossil record clearly shows a huge loss of life but not what caused it. Over the years, a number of possibilities have been put forward, but the cause of two of the big five – the end-Neoproterozoic and end-Triassic – remains uncertain.

CONTINENTAL MOVEMENTS. During the Permian and Triassic, all continents were fused into a supercontinent, Pangaea. At one time, the end-Permian mass extinction was linked to this, based on the suggestion that fusion of continents removes intercontinental seas, each with its own unique fauna, and allows land animals and plants to mix. It now seems, however, that such movements are too slow to lead to massive species loss.

ICE AGES. The late Ordovician mass extinction has been explained as a consequence of a massive ice age, particularly the growth of a huge southern ice cap (see map, right). As the ice spread, species migrated towards the equator and warm-adapted species may have disappeared. Sea levels fell dramatically, reducing many inland seas and causing widespread extinction.

ANOXIA. The late Devonian extinction has been linked to a lack of oxygen in the ocean, possibly caused by sudden temperature changes or massive increases in the supply of sediment from the land caused by the rise of terrestrial plants.



ANDREI SPIRACHE/GETTY

IS THERE A COMMON PATTERN?

In the 1980s, as the Alvarez hypothesis gained ground, it seemed reasonable to assume that all mass extinctions were caused by impacts. Though there have been numerous "discoveries" of craters and other impact signatures coinciding with the other mass extinctions, none has stood up to scrutiny. It now seems that the KT event was unique – the only mass extinction caused by an impact. In fact, we now think that each mass extinction had its own unique cause.

Another idea that was fashionable in the 1980s was that mass extinctions are periodic. Some palaeontologists claimed to have found patterns in the fossil record showing a mass extinction every 26 million years, and they explained this by suggesting that a "death star", dubbed Nemesis, periodically swings into our solar system and perturbs the meteorite cloud. But Nemesis has never been found and evidence for this pattern is now widely doubted.

Common features have emerged, however. For example, it does seem that some species are more vulnerable to extinction than others. Large body size makes animals especially susceptible as it is associated with high food requirements, large feeding range and small population size. Species with specialised diets or limited distribution are also likely to suffer. In contrast, the survivors tend to have large population sizes, live in many habitats in many parts of the world, and have a varied diet.

This is not to say that mass extinctions are highly selective. David Raup at the University of Chicago famously characterised the death of species during mass extinctions as the result of "bad luck rather than bad genes", meaning that the normal rules of natural selection break down. Their success – or lack of it – in normal times has little bearing on their chances of survival when the meteorite hits or the volcano erupts.

This holds lessons for current and future extinctions (see back cover). For example, if humans destroy habitats wholesale then all species are vulnerable, whatever their size, diet or habitat.


BRISTON UNIVERSITY

Michael J. Benton

Michael J. Benton is professor of vertebrate palaeontology at the University of Bristol in the UK. His research focuses on the end-Permian mass extinction

NEXT
INSTANT
EXPERT

Stuart Haszeldine
& Vivian Scott
CARBON
CAPTURE
2 April

APOCALYPSE NOW?

It is often said that we are living through the sixth mass extinction, this one induced by human activity. The point is well made: the present biodiversity crisis appears to be comparable in scale to many of the biotic crises of the past.

There can be no doubt that many species have gone extinct on our watch. We know, for example, that the last great auk was killed by collectors in 1844, the dodo was last seen in 1662 and the last passenger pigeon died in a zoo in 1914. Hunters shot the last quagga, a zebra-like wild horse, in the 1870s and the last thylacine – or Tasmanian tiger – died in captivity in 1936.

These examples, however, tell us little about the scale of the crisis. For that we have to aggregate known historical extinctions. Unfortunately the records are not good, but we do know that 130 species of bird were driven to extinction by hunting between 1500 and 2000. This gives us a starting point.

There are currently some 10,000 bird species, so these extinctions represent a loss of 1.3 per cent of species in 500 years, or 26 extinctions per million species per year – much greater than the background rate of extinction (see page ii).

Even this could be an underestimate because many other bird species might have become extinct in that time without being recorded. What is more, extinction rates have arguably risen in recent years due to habitat destruction. Taking these factors into account has yielded an alternative figure of about 100 extinctions per million species per year.

If we assume this applies to all of the estimated 10 million species on Earth, total losses might now be 1000 species per year, or three species every day. This is a very rough estimate but it suggests claims of a sixth mass extinction are not exaggerated.

It could of course be objected that this rate of loss cannot proceed inexorably. The optimist might argue, for example, that most of the species so far driven to extinction were already rare or vulnerable, and that they were hunted without mercy in less enlightened times. There is surely some truth in these assertions: it is unlikely that globally distributed species such as sparrows, rats or mice would be so easy to exterminate as the dodo. Further, no nation would allow hunters to slaughter animals as systematically as was done by Victorian-age hunting parties.

However, despite tighter controls on hunting and increasing conservation efforts, pressure on natural habitats has never been more extreme.

While it is frustratingly hard to put precise figures on current rates of species loss, uncertainties should not be seen as a reason for complacency. The fossil record shows how devastating mass extinctions are and that, although life does recover, it takes millions of years to do so. The study of mass extinctions, and comparisons with the modern world, show that we are almost certainly responsible for another mass extinction, and the living world could soon be a much-diminished place.

RECOMMENDED READING

Mass Extinctions and their Aftermath by Tony Hallam and Paul Wignall (Oxford University Press)

When Life Nearly Died: The greatest mass extinction of all time by Michael J. Benton (Thames & Hudson)

T. rex and the Crater of Doom by Walter Alvarez (Princeton University Press)

Vanishing Life: The mystery of mass extinctions by Jeff Hecht (Prentice Hall & IBD)

Cover image: Jonathan Blair/NGS