NEW

THE MESOZOIC WORLD
DINOSAUR ANATOMY
BEHAVIOUR & ADAPTATIONS
EXTINCTION EVENTS
FOSSIL HUNTING

UNDERSTANDING Dinosaurs

Digital Edition

FIRST EDITION

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Welcome

In an editorial excavation, we have carefully dug through the archives of How It Works and Science Uncovered magazines to unearth this compilation of fascinating dinosaur features.

Throughout this book, you will discover how dinosaurs dominated the planet for millions of years. From terrifying predators like T rex to towering titans like Apatosaurus, learn how these incredible creatures survived in the Mesozoic era, before a fateful extinction event brought their reign to an end. Also inside, you'll learn about advancements in paleontology, and how our understanding of dinosaur anatomy, physiology and behaviour has evolved over the past few decades.

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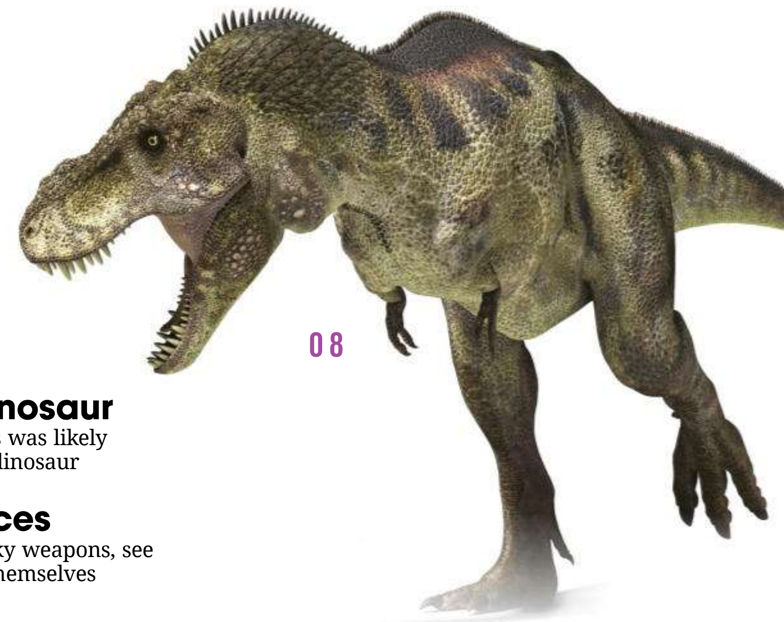

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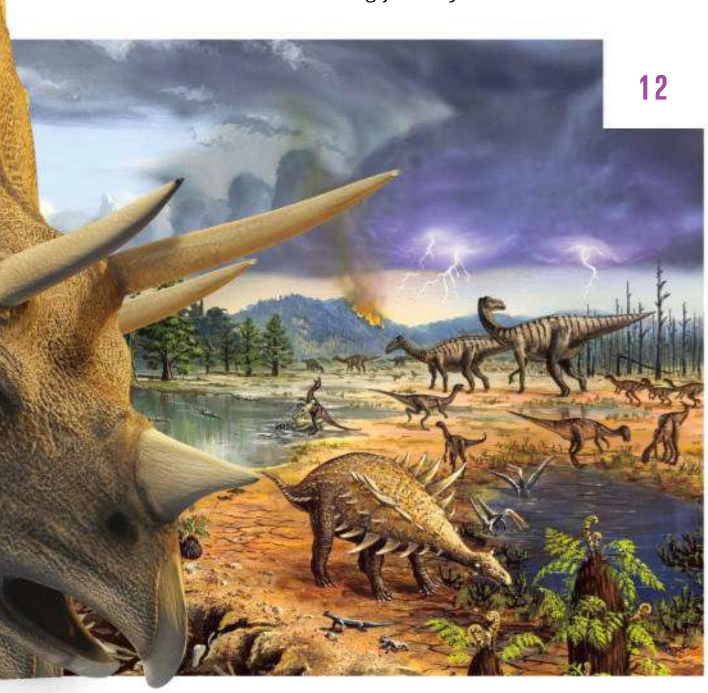

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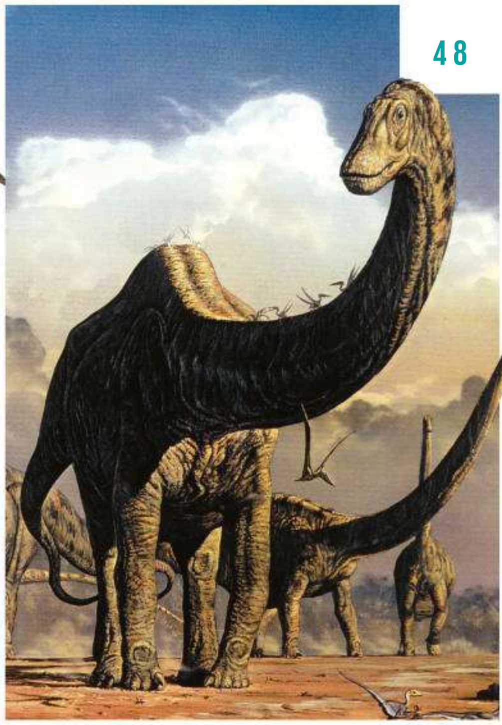

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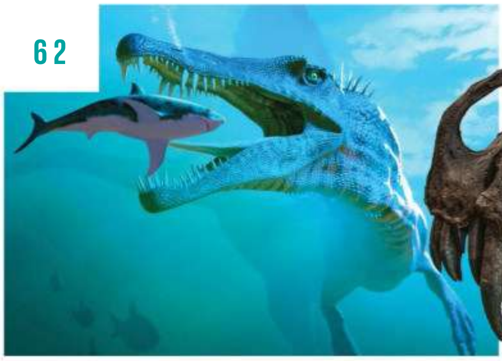

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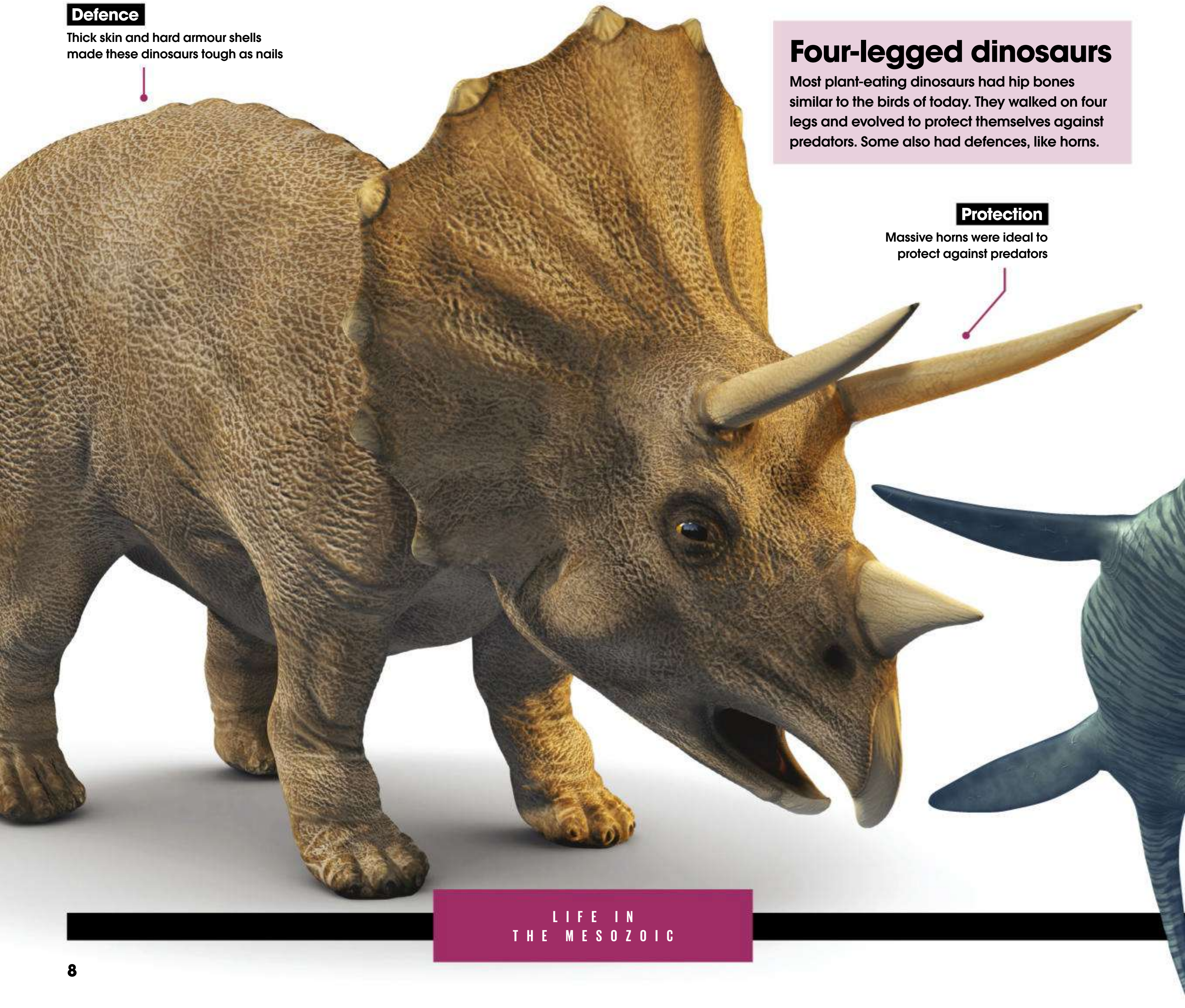
Life in the Mesozoic

What were dinosaurs?

Dinosaurs were a group of reptiles that first evolved over 230 million years ago, and went on to dominate Earth

Dinosaurs roamed the Earth for over 160 million years, becoming the dominant vertebrates on land. Although fossilised dinosaur remains have been discovered throughout human history, they were not studied in enough detail to fully understand what creatures they belonged to. Dinosaurs were only described scientifically in the early 19th century; it was British palaeontologist Sir Richard Owen who coined the taxon Dinosauria in 1842.

The word dinosaur means 'terrible lizard', but the term is misleading – dinosaurs are not lizards, but part of a separate group of reptiles altogether. They first evolved in the Triassic period, approximately 243 and 233 million years ago, on the super-continent of Pangaea. Over time, continental drift occurred and Pangaea broke up into smaller landmasses. This led to dinosaurs strongly diversifying as they evolved in different environments around the world.

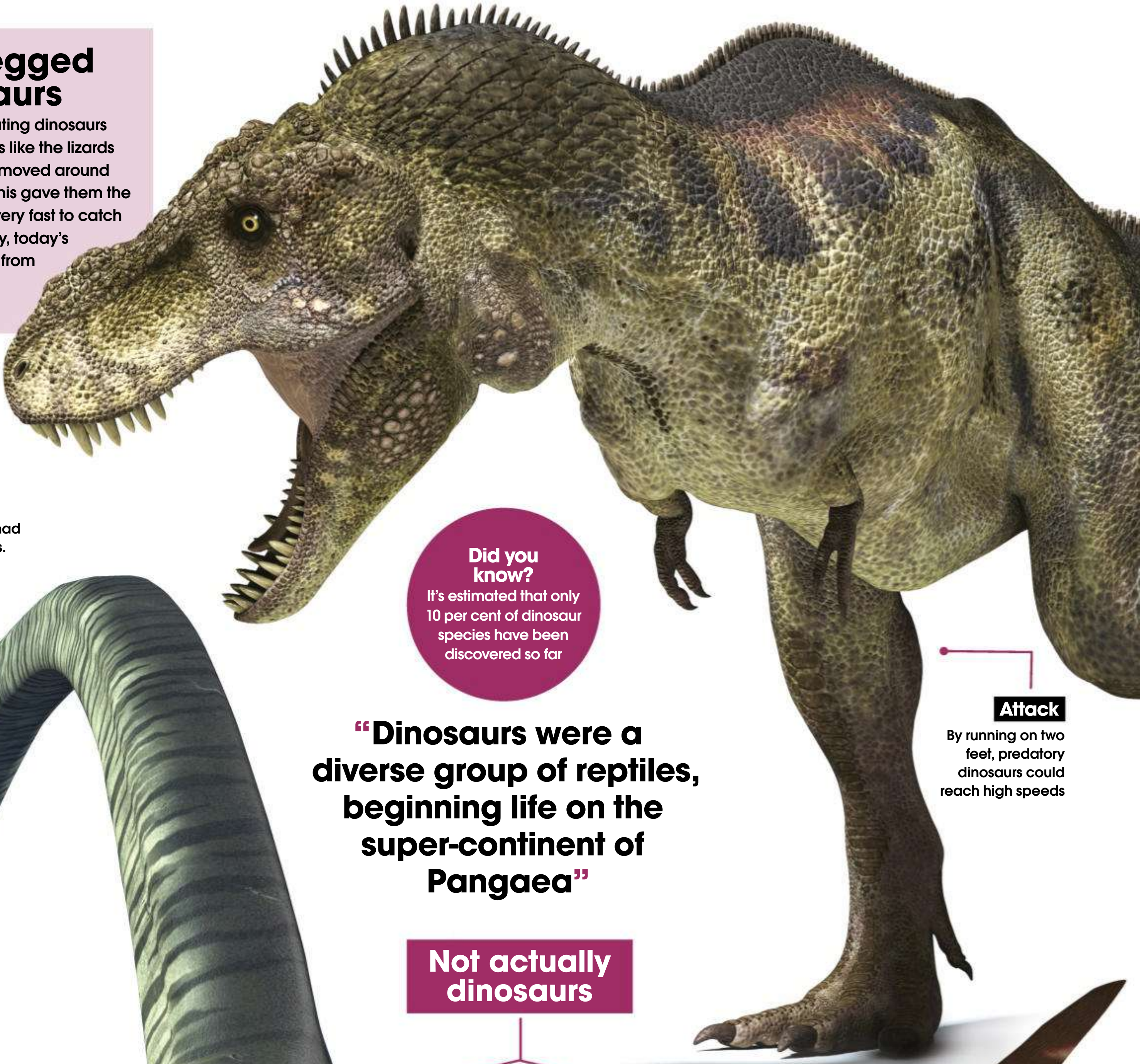


Four-legged dinosaurs

Most plant-eating dinosaurs had hip bones similar to the birds of today. They walked on four legs and evolved to protect themselves against predators. Some also had defences, like horns.

Two-legged dinosaurs

Most meat-eating dinosaurs had hip bones like the lizards of today and moved around on two legs. This gave them the ability to run very fast to catch prey. Strangely, today's birds evolved from lizard-hipped dinosaurs.



Plesiosaurs

Some plesiosaurs had long, flexible necks. They used these to catch nimble fish

Did you know?

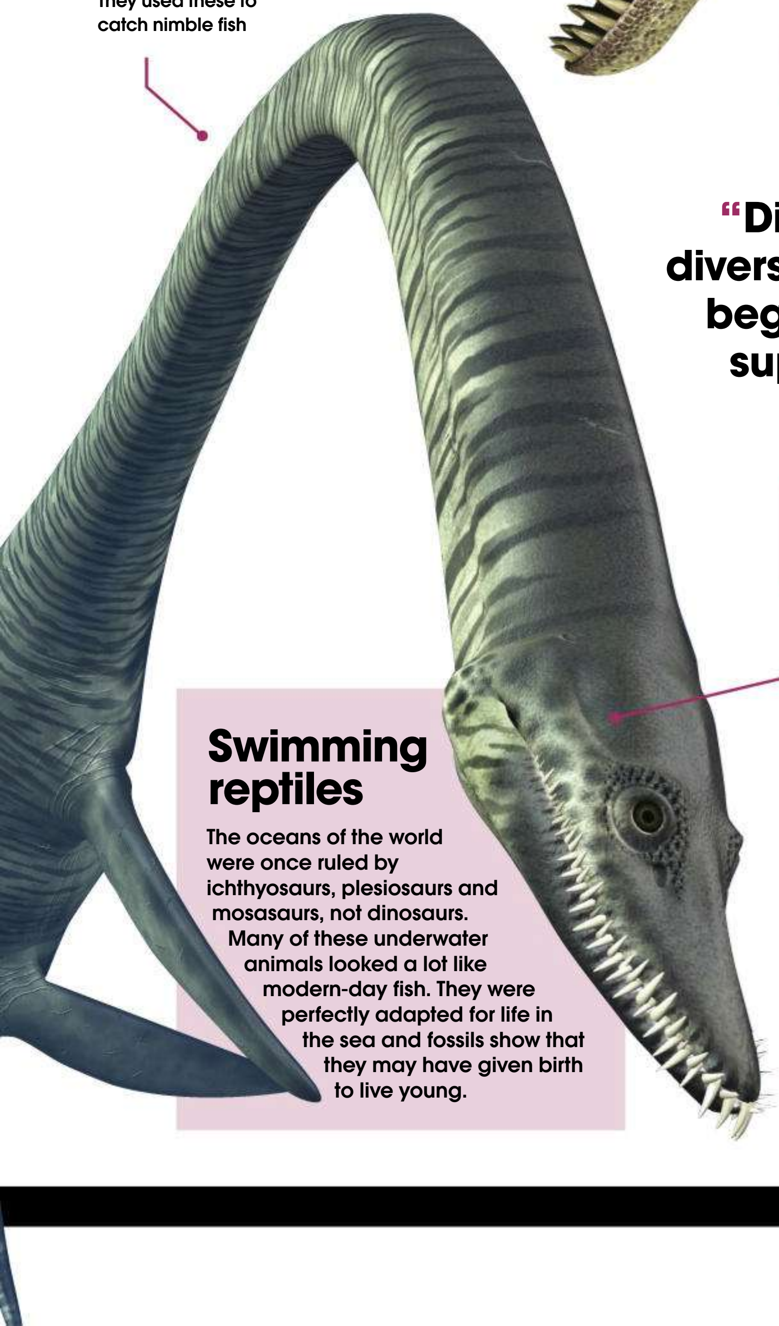
It's estimated that only 10 per cent of dinosaur species have been discovered so far

> **"Dinosaurs were a diverse group of reptiles, beginning life on the super-continent of Pangaea"**

Attack

By running on two feet, predatory dinosaurs could reach high speeds

Not actually dinosaurs

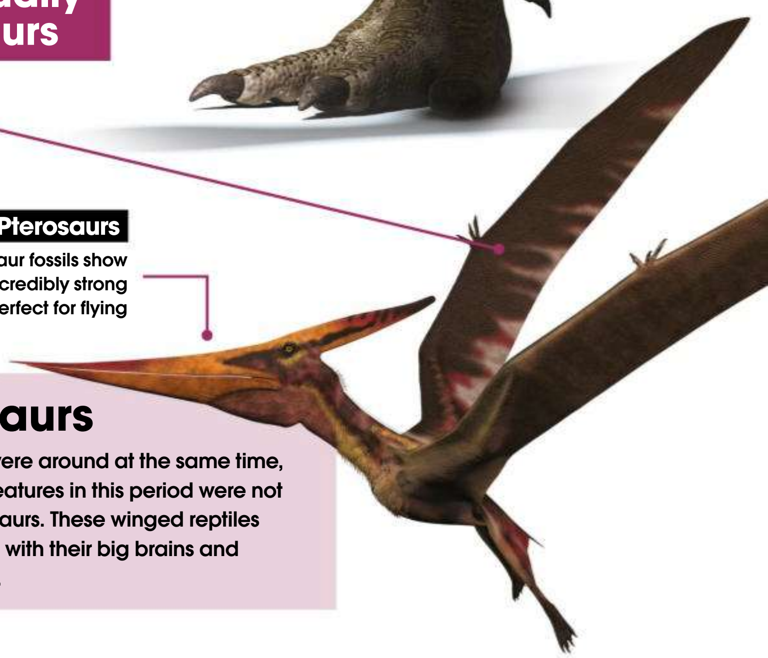


Swimming reptiles

The oceans of the world were once ruled by ichthyosaurs, plesiosaurs and mosasaurs, not dinosaurs. Many of these underwater animals looked a lot like modern-day fish. They were perfectly adapted for life in the sea and fossils show that they may have given birth to live young.

Pterosaurs

Many pterosaur fossils show they had incredibly strong muscles, perfect for flying



Pterosaurs

Though they were around at the same time, most flying creatures in this period were not actually dinosaurs. These winged reptiles ruled the skies with their big brains and deadly beaks.

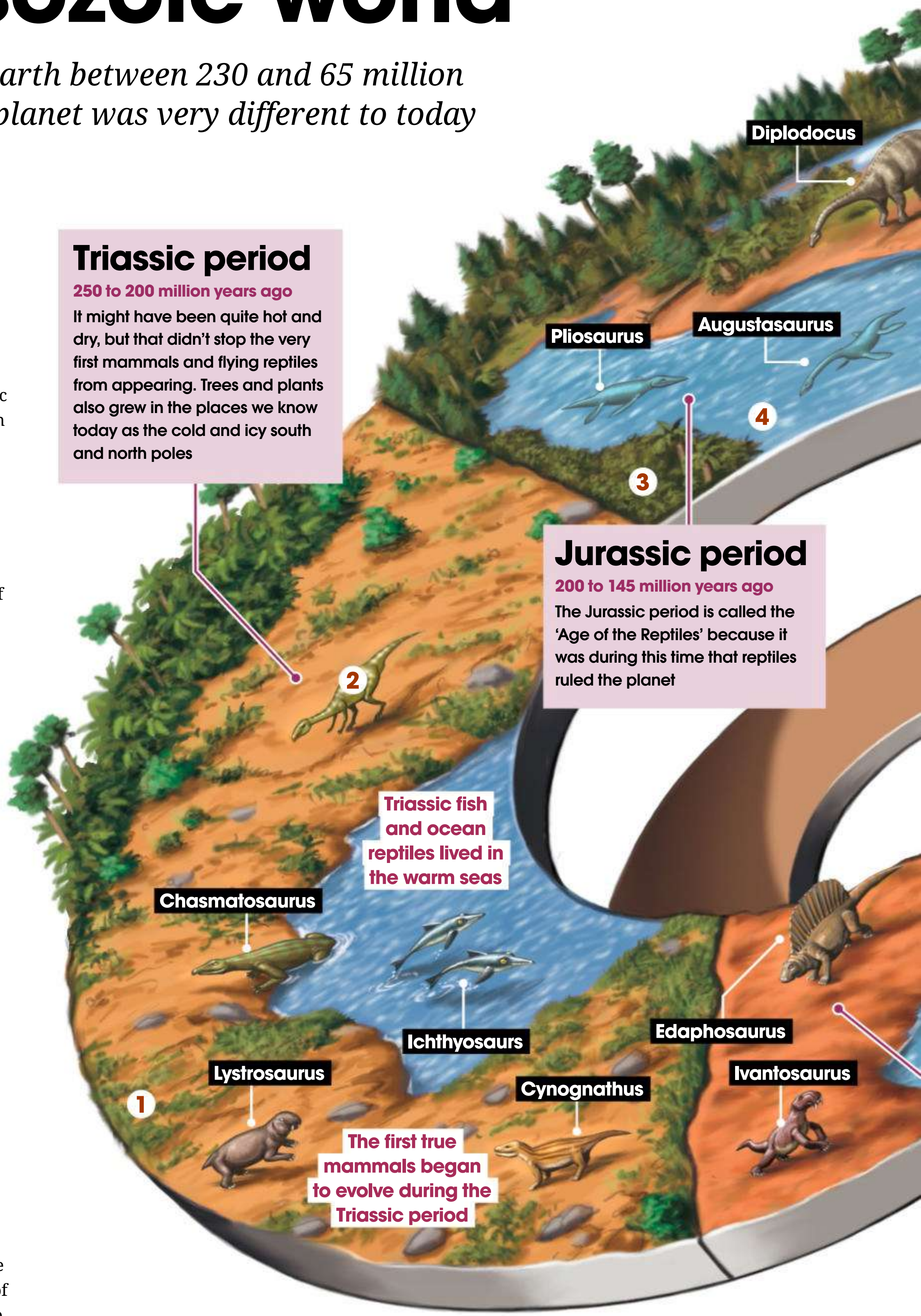
The Mesozoic world

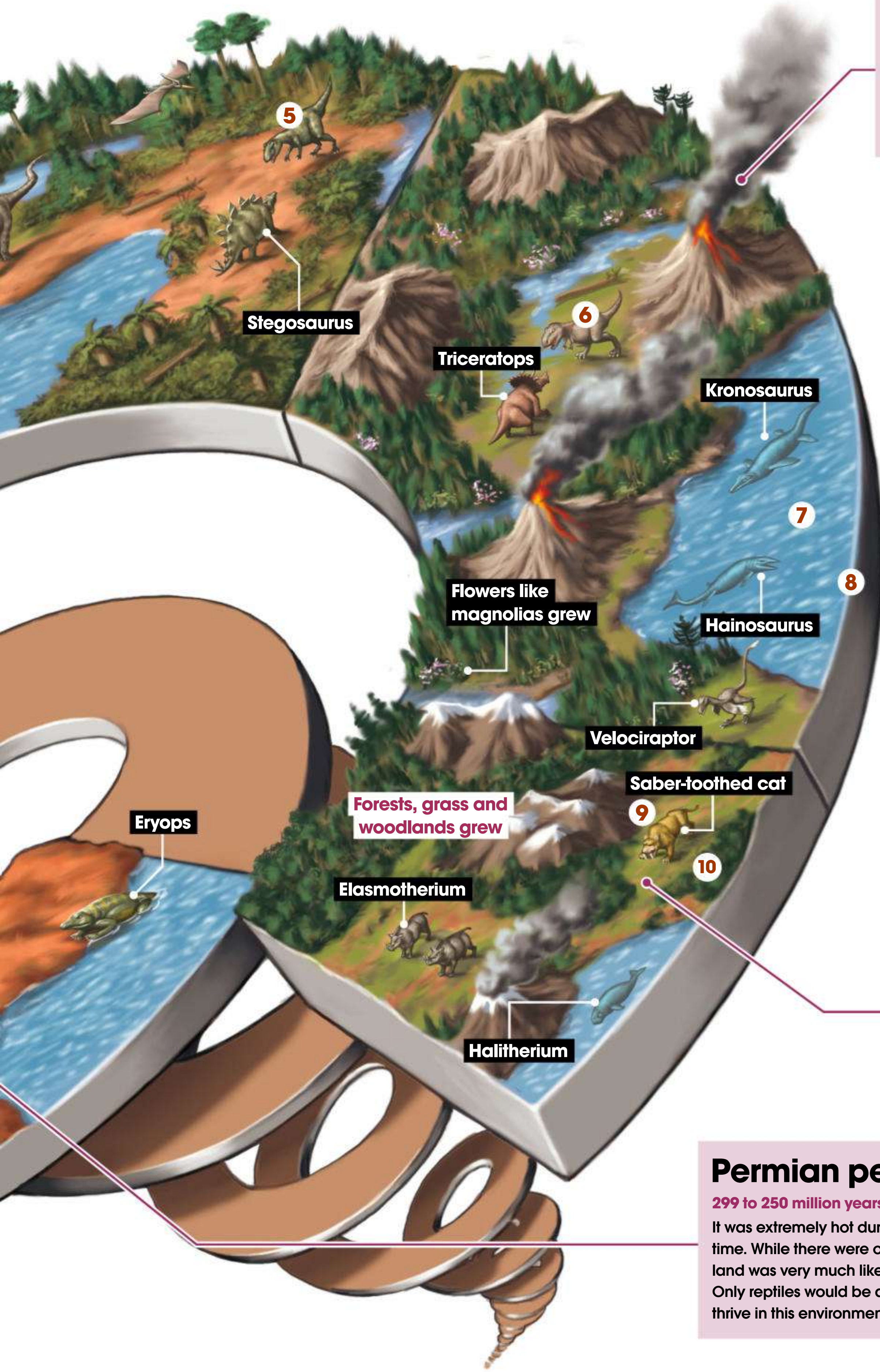
Dinosaurs roamed Earth between 230 and 65 million years ago, when our planet was very different to today

The ultra-dry climates of the Permian era, and the subsequent destruction of the ancient coal swamps that were home to a great many Carboniferous plants, meant that the Mesozoic (or 'middle life') era signalled something of a recovery period in Earth's history. Comprising the Triassic, Jurassic and Cretaceous periods, the Mesozoic era was less dry but was still swathed in high global temperatures, and the now-empty ecosystems on the land were soon taken over by evolving mammals and dinosaurs. Meanwhile, beneath the oceans, new corals appeared and various sea urchins began to diversify and thrive, having been almost driven to the point of extinction at the end of the Permian era.

Some estimates put some of the more tropical temperatures during the start of the Triassic period (at the beginning of the Mesozoic era) as high as 38°C (100°F), and at this point the world's land masses were still combined in one large supercontinent called Pangaea. During the Triassic period, Pangaea gave rise to climatic zonation, with some areas becoming extremely dry and others experiencing monsoon-like conditions. As a consequence of this climatic zonation, plants began to separate into northern and southern realms.

By the time of the Jurassic period, global temperatures had dropped to around 30°C (86°F) and Pangaea had separated into northern and southern parts. The oceans as we know them today really started to take shape during the Cretaceous period – so-called because of the large chalk content in the shallow seas as a result of the build up of algae skeletons. Following the major extinctions at the end of the Cretaceous period, mammals – which previously tended to be small and insignificant compared to the dinosaurs – were now able to exploit many of the vacant ecosystems and gradually come to dominate the planet.





Cretaceous period

145 to 66 million years ago

Sea levels were high during the warm Cretaceous period. Dinosaurs ruled the land, while other types of creatures swam the seas

1 High temperatures
It might have been very hot, but some places had rain

2 The first dinosaurs
Staurikosaurus is one of the very first known dinosaurs

3 Flora
Lush jungles covered much of the land

4 Continents
Around the world, land moved to make more coastlines

5 Predators
Very large land predators like Allosaurus preyed on other animals

6 T rex
Tyrannosaurus rex lived during the Cretaceous period

7 Sharks
Sharks were common in the seas

8 Cooling down
The Cretaceous period was cooler than earlier periods

9 Mammals
The Tertiary period was called the 'Age of the Mammals'

10 Palm trees
Palm trees grew as far north as Greenland before the middle and end of the Tertiary period

Tertiary

66 to 2.5 million years ago

The dinosaurs had been wiped out by a great asteroid by this time. In their place, other animals like the saber-toothed cat evolved

Permian period

299 to 250 million years ago

It was extremely hot during this time. While there were oceans, the land was very much like a desert. Only reptiles would be able to thrive in this environment

Did you know?
Lots of dinosaurs couldn't survive the 60°C heat of the Triassic period

Dinosaur habitats

Dinosaurs lived all over the world, from dry, dusty deserts to wet, sweaty swamps. Explore four different habitats that dinosaurs called home…

When dinosaurs first inhabited the Earth back in the Triassic Period (250-200 million years ago), the land they existed on was considerably different to what we know today. All continents formed a single landmass called Pangaea and the climate was hot and dry, causing much of the land to be covered by deserts – which is where dinosaurs first evolved. A series of earthquakes and volcanic eruptions caused Pangaea to split, and many of the dinosaurs became extinct. This led to the Jurassic period and a cooler climate, out of which dense, green jungles took shape – the habitat for different species of dinosaur. Read on to discover which types of dinosaur flourished in each of the different environments.

First dinosaurs

The weather of the Triassic period helped dinosaurs to develop. Their bodies were much better suited to hot and dry conditions compared to mammals

Plants

Only plants that could live without lots of water survived in these areas. There wasn't much for herbivores to eat

Did you know?

The extinction event that killed the dinosaurs is one of five major events to have changed the Earth

Triassic desert

250 to 200 million years ago

Dinosaurs first appeared during the Triassic period. Earth was hot, dry and covered in deserts

Throughout the Mesozoic era, which comprised the Triassic, Jurassic and Cretaceous periods, much was changing on and in the Earth's lands and seas.

The Triassic period was a time of recovery after the devastation, in terms of the fauna and flora, that brought to a close the Permian period. The high global temperatures and the empty ecosystems on the land meant that dinosaurs and mammals evolved during the Triassic period, while the oceans saw sea urchins begin to diversify, having been driven almost to the point of extinction at the end of the Permian period.

Global warming in the early Triassic period produced one of the hottest periods in Earth's history. The resulting deserts were home to a variety of dinosaurs, such as the Euparkeria. Fossil finds in what is now the Karoo Desert of South Africa indicate that these carnivorous creatures were blessed with speed and agility thanks to longer back legs that allowed them to stand upright. An enlarged sinus cavity also suggests they had a fine sense of smell, which would have been ideal for sniffing out prey in its open desert surrounds.

Triassic forest

250 to 200 million years ago

The weather was milder at the north and south poles. It was drier, so large forests grew

Trees

Most trees in these forests were tall with tough leaves. They were evergreens so didn't lose their leaves over winter

No ice caps

Even the north and south poles were warm. They weren't icy and frozen like Antarctica and the Arctic are today

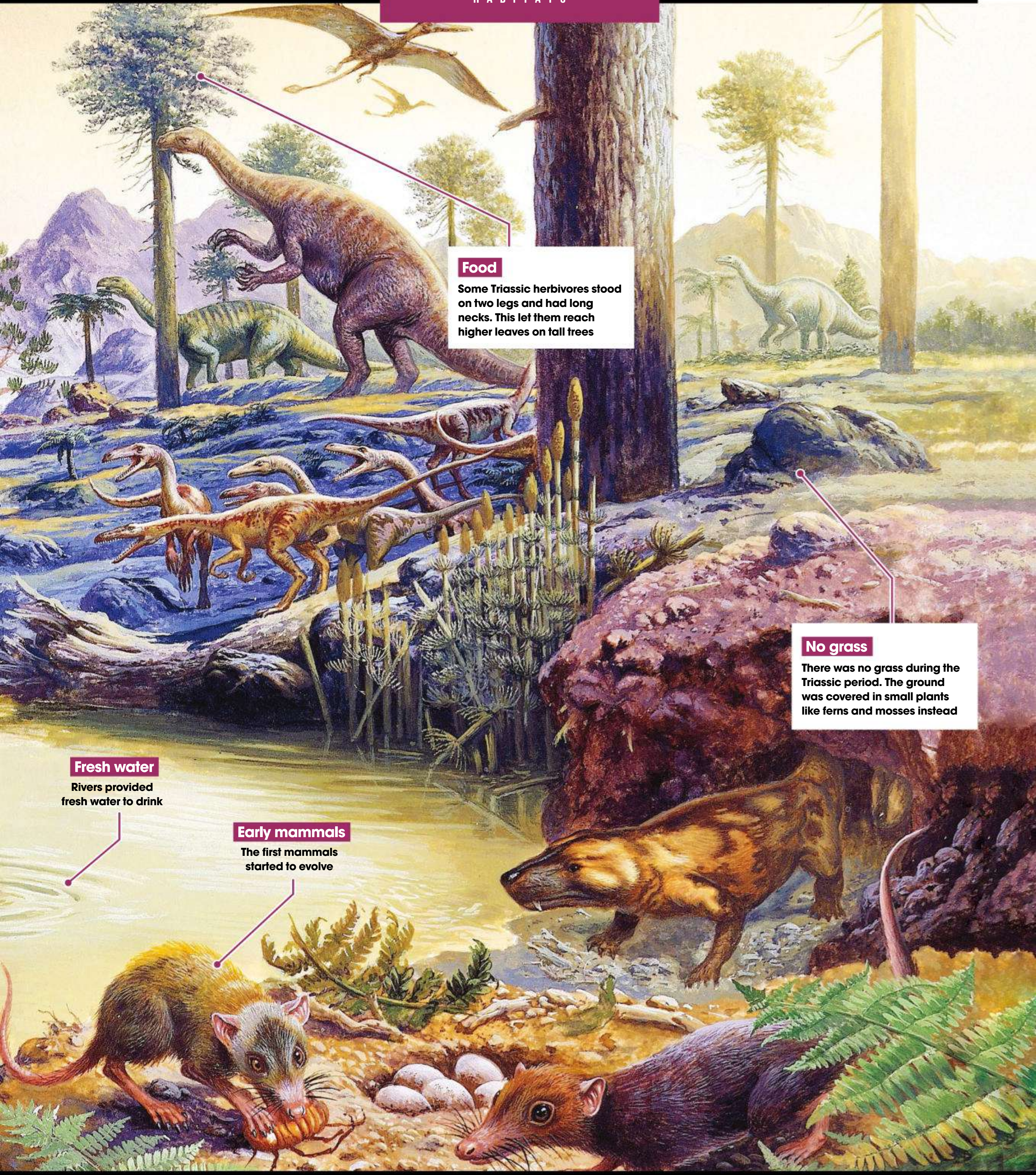
The presence of coal deposits in the high northern and southern latitudes suggests that these regions were much wetter than the desert-like lower latitudes, so dense, forest-like vegetation was able to grow.

These jungles were home to Rauisuchians, such as the Effigia, and Sauropodomorphs, such as the Plateosaurus, whose long neck and weight-bearing bone structure allowed it to stand upright, which in turn enabled it to feed off plants that were out of reach of other herbivorous dinosaurs.

During the Triassic period, the oceans and continents were starting to change. The land mass of the supercontinent Pangaea was at its largest due to lower sea levels and it had started to move northwards and rotate anti-clockwise, ultimately breaking up to give the Earth a slightly more familiar look. Fossils from the mid-to-late Triassic period indicate that the seas and oceans housed a wide range of marine-based reptiles and ammonites that began to thrive in this period.

Did you know?

Most of the trees in Triassic forests were conifers. They evolved 300 million years ago


Food
Some Triassic herbivores stood on two legs and had long necks. This let them reach higher leaves on tall trees
No grass
There was no grass during the Triassic period. The ground was covered in small plants like ferns and mosses instead
Fresh water
Rivers provided fresh water to drink
Early mammals
The first mammals started to evolve

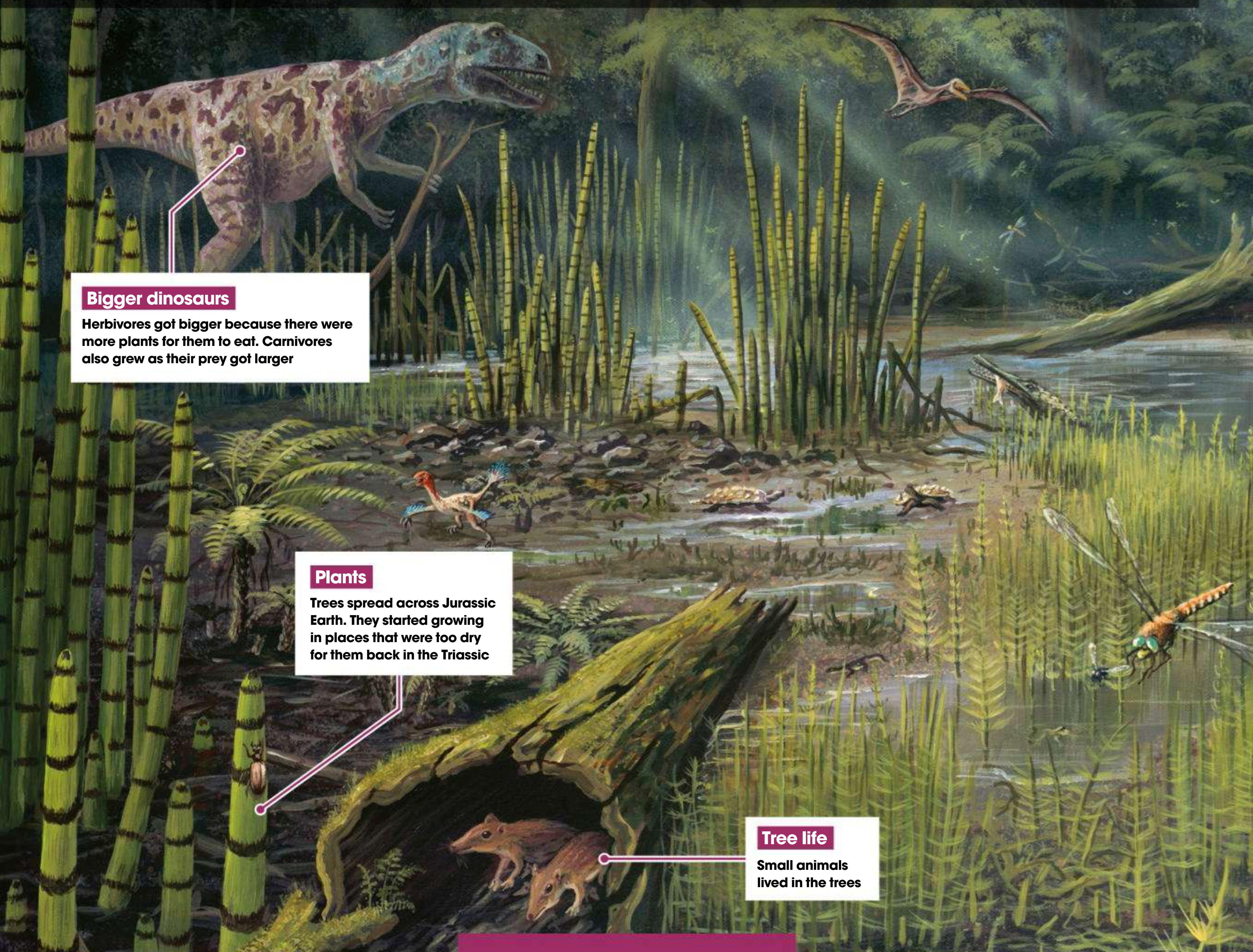
Jurassic swamp

200 to 145 million years ago

Sea levels were higher during the Jurassic period. Some land got flooded, which created muddy swamps

During the late Jurassic period, the Earth's temperatures had cooled to around 30°C (86°F), declining still further later on in the period, and the Earth began to experience seasonality, with extremely hot summers and unbearably cold winters. Nevertheless, the Jurassic period is when life on Earth thrived, with large dinosaurs roaming the land, huge reptiles dominating the seas and winged reptiles ruling the skies. The oceans were teeming with new predators, including ammonites, belemnites and a range of shell-crushing fish.

One of the most formidable predators of this period was the Allosaurus. With a large skull full to the back with sharp, serrated teeth and three large claws on either hand that may have been used to grip onto its prey, many believe that the Allosaurus hunted stegosaurs, ornithopods and sauropods – creatures that devoured the plants native to the planet's swamps. Stegosaurus is perhaps the best-known stegosaur and was so-called because of the strange, diamond-shaped plates running down its back (Stegosaurus means 'plated lizard'). While many assume that these plates were for defence, the two pairs of long spikes that projected from the tip of the tail were much more likely for this purpose, rendering the plates little more than fancy decorations.



Weather

Regular rainy seasons kept the soil damp. This watered ferns and other small ground plants that herbivores could consume

Continents moving

As Pangaea split up, the new continents had different habitats like swamps. Animals evolved quickly to survive in these new areas

Did you know?
Pangaea formed approximately 300 million years ago

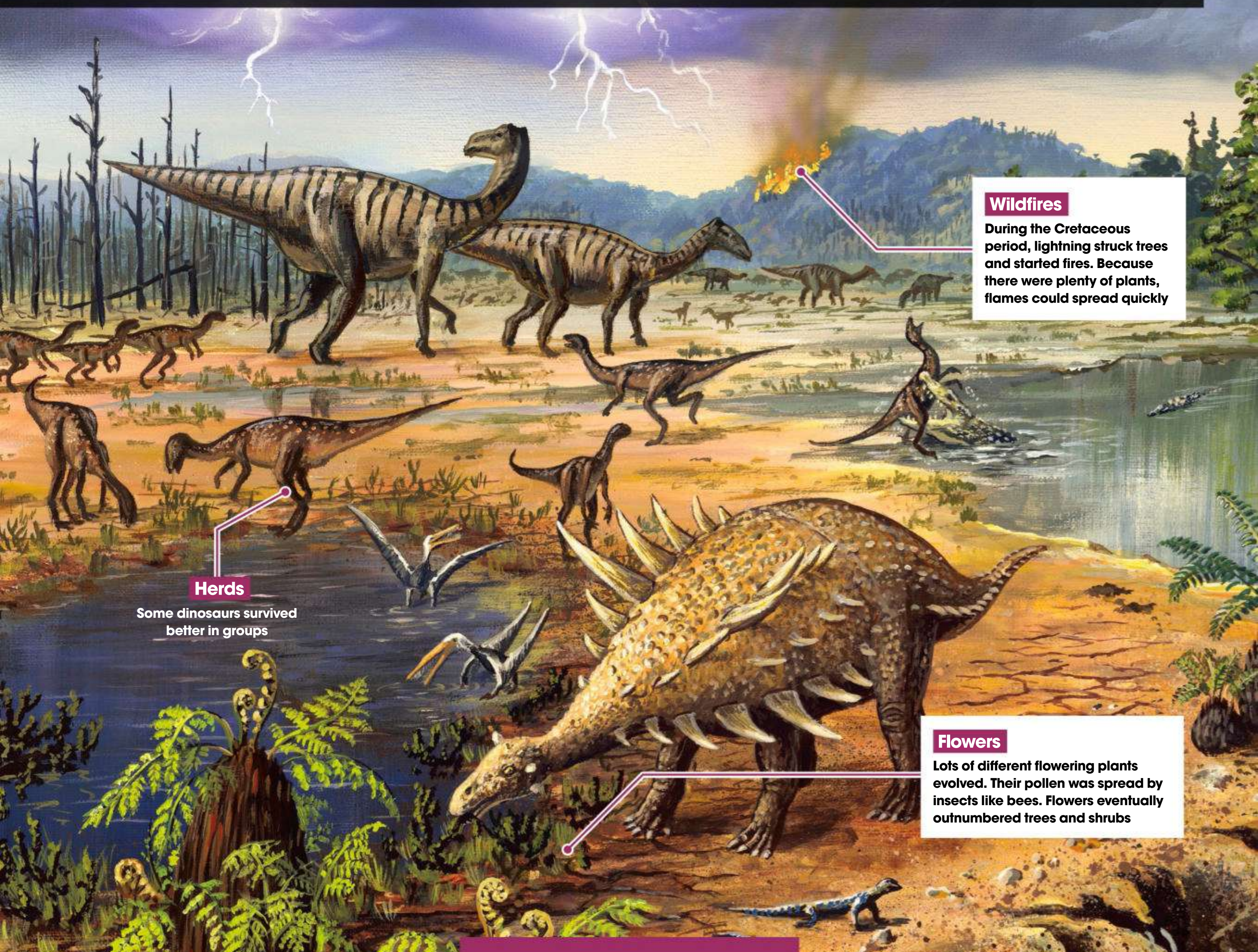
Cretaceous plains

145 to 66 million years ago

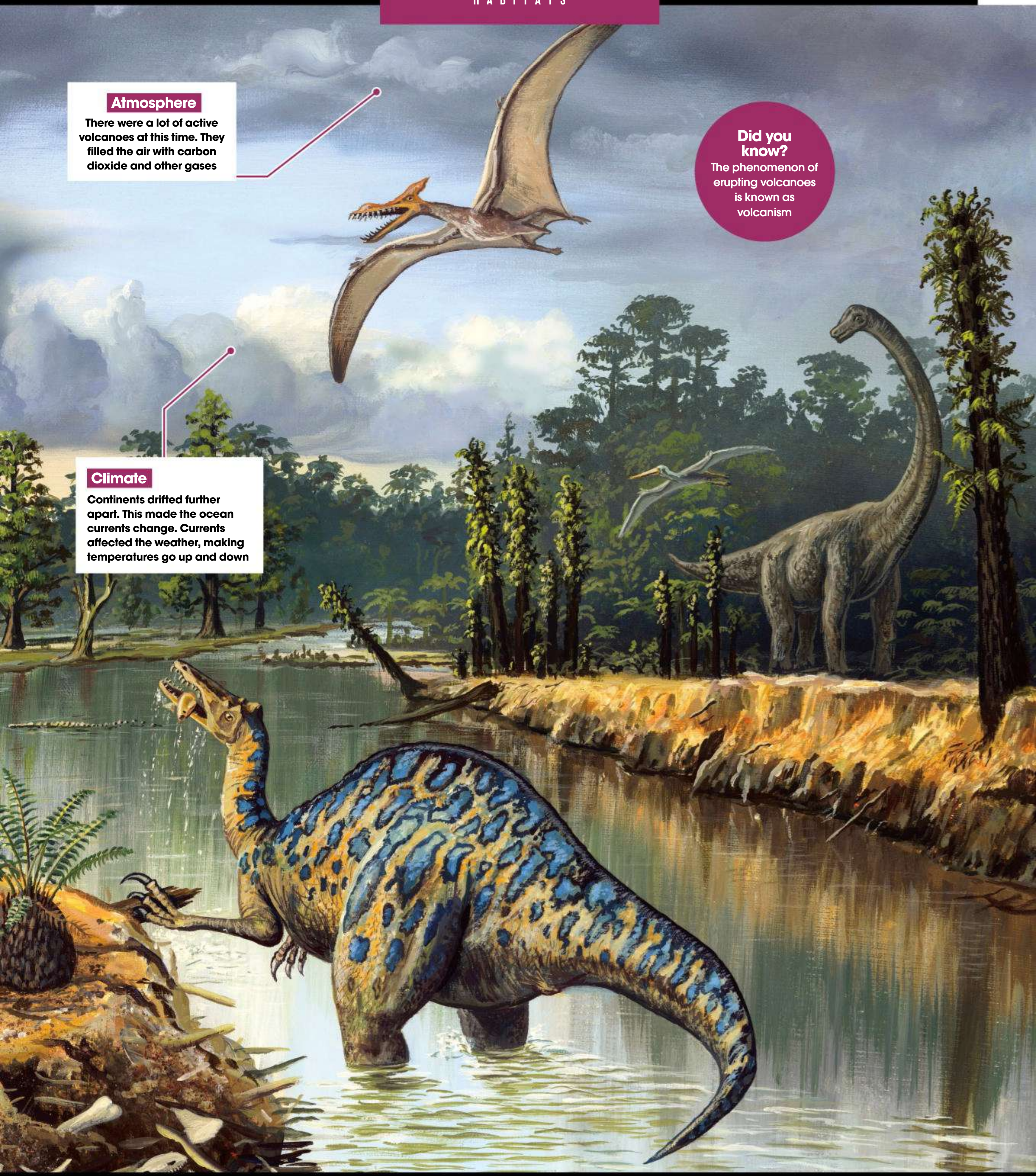
Life was not easy on the Cretaceous plains. Dinosaurs faced many changes to their habitat

The climate of the Cretaceous period consisted of global temperatures of around 10°C or 50°F higher than today and high atmospheric carbon dioxide levels. It was something of a greenhouse world. The high sea levels (approximately 200-300m higher than today) meant that swamp-like plains existed on the lower latitude areas where crocodylomorphs, such as the Simosuchus and Deinosuchus, began to thrive. The Deinosuchus, a member of the alligatoridae family that includes modern day alligators, weighed up to ten tons and was one of the most ferocious predators in North America. In fact, its habitat overlapped with tyrannosaurids, such as Daspletosaurus; in these ecosystems it was the powerful alligatorid, not the tyrannosaurids, that dominated.

Also during the Cretaceous period, the skies were inhabited by colossal pterosaurs, such as the Quetzalcoatlus. These beasts rank as the largest flying creatures of all time, with a wingspan larger than many small planes. However, thanks to a complex system of air sacs inside its bone structure, the Quetzalcoatlus weighed no more than 250kg. They were agile and fast in the air, making catching prey easy.



LIFE IN THE MESOZOIC



Atmosphere
There were a lot of active volcanoes at this time. They filled the air with carbon dioxide and other gases

Did you know?
The phenomenon of erupting volcanoes is known as volcanism

Climate
Continents drifted further apart. This made the ocean currents change. Currents affected the weather, making temperatures go up and down

Polar dinosaurs

Evidence shows that some dinos survived cold, dark winters

For a long time, both experts and the public believed dinosaurs only thrived in tropical regions. But imagine everyone's surprise if the next Jurassic Park movie had our heroes running around in thick winter coats for a change. It may seem unlikely, but our understanding of dinosaurs is changing all the time; fossil evidence has shown that dinosaurs also managed to survive in much colder environments than previously thought.

One such chilly habitat was the landmass now known as Australia. Nowadays this region is far from cold, but 65-100 million years ago it was considerably further south, resting right next to the continent of Antarctica.

So how did dinosaurs survive in these conditions? A previous theory suggested that they migrated to warmer climates as the coldest season descended. But this has now largely been debunked; the 'over-wintering' theory, which involves dinosaurs either enduring the cold or tucking in for winter, is now in favour.

Some of the smaller dinosaurs, in particular, are believed to have possibly burrowed into a den for winter hibernation – much like the polar bears of today. But we know that this wasn't the case for all prehistoric beasts. Analysis of polar dinosaur bones has shown that they grew all year round, which suggests that these animals did not spend months sleeping.

Fortunately for these animals, the poles weren't quite as cold as they are today, but they did experience prolonged, dark winters. This made it difficult for plants to thrive, but some hardy vegetation could provide nourishment for herbivores, which in turn was good news for the carnivores, because they had more prey to hunt.

The duck-billed giant

The fossil of a nine-metre-long herbivore unearthed in a remote part of Alaska in 2015 is the furthest north a polar dinosaur has ever been found. Paleontologists confirmed this newly discovered species after studying a set of fossilised remains, and it displays distinct differences to its relatives found further south.

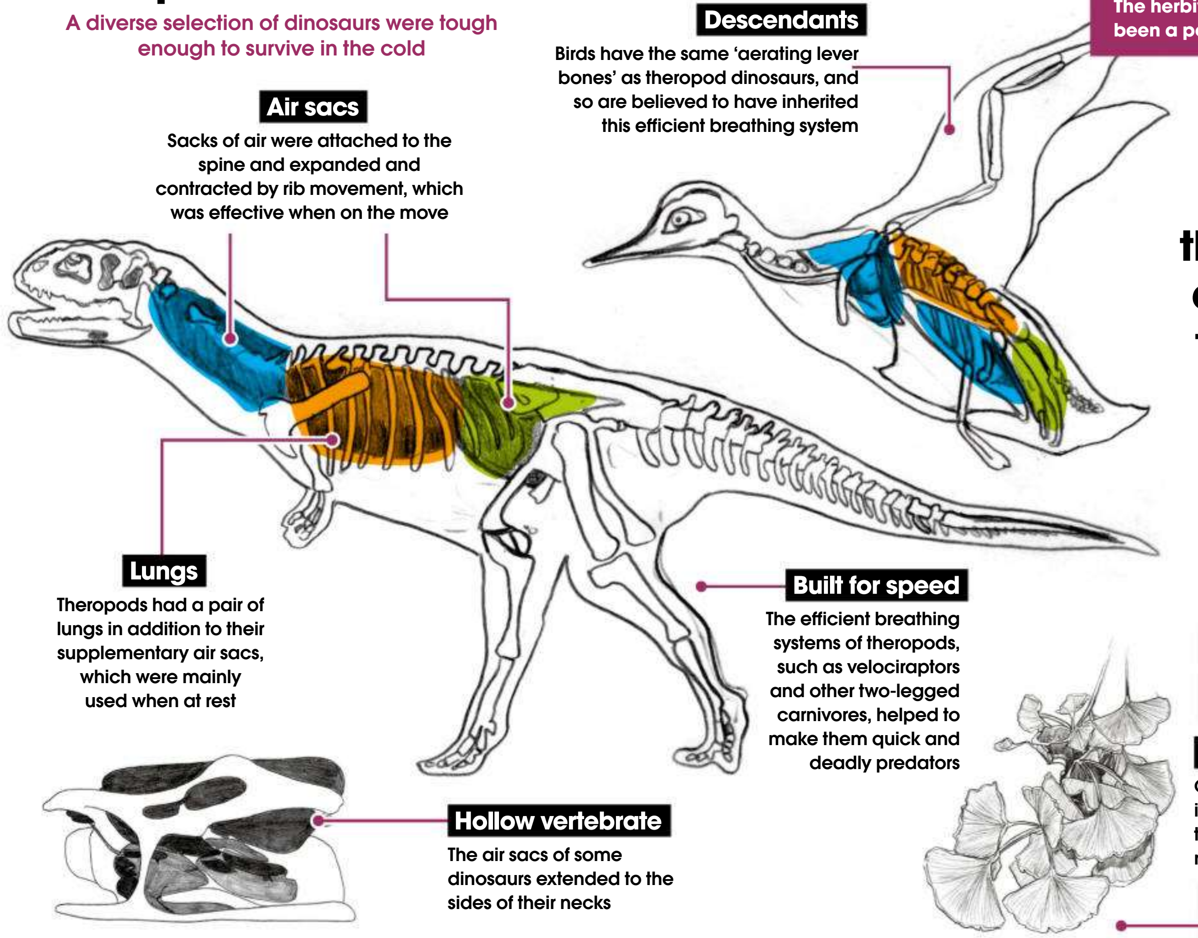
It's believed the Arctic hadrosaur stood on two of its four legs to reach food from up high. An interesting duck-billed facial structure and hundreds of teeth helped this gigantic beast to tackle the coarse forage.

As well as its ability to devour the bountiful vegetation, the hadrosaur was able to endure months of darkness and a drop in temperature over winter – and perhaps even snow. These exciting findings help to paint the picture of polar dinosaurs, solidifying their reputation as tough and adaptable animals.

The herbivorous Arctic hadrosaur may have been a permanent resident of polar regions

Adapted for survival

A diverse selection of dinosaurs were tough enough to survive in the cold



"Fortunately for these animals, the poles weren't quite as cold as they are today"

Limited sunlight
Some polar dinosaurs had enlarged optic lobes, which adapted their vision for long periods of winter darkness

Warm-blooded?
If some dinosaurs could control their body temperature internally, rather than relying on the environment for heat, they would have endured the cold better

A warmer Earth
Although polar dinosaurs were equipped for the cold, it's unknown whether they would have been able to cope in the incredibly harsh polar regions of today. Modern day climates experience temperatures so low that only the most resilient life can survive, which is quite a contrast to the land of lush vegetation that was able to grow during the Mesozoic era.

Dinosaurs were able to enjoy higher temperatures thanks to the much greater levels of carbon dioxide in the atmosphere. This warmed the planet, melted the poles, and allowed life to prosper. However, between the end of the dinosaur era and the early years of humankind, natural processes lowered the carbon dioxide levels, temperatures fell, and the poles froze once more.

Increased temperatures from high carbon dioxide levels made it easier for flora and fauna to flourish near the poles

Fodder
The poles were warmer during the Mesozoic era than today, so vegetation flourished during the summer

Insulated
A thick body of plumage would have kept the dinosaurs warm

Burrowers
Smaller dinosaurs may have hibernated or denned themselves in throughout the coldest periods

Did you know?
Plants in prehistoric Antarctic forests could hotosynthesise for 24 hours a day during the polar summer

The Jurassic food chain

An example of predator-prey dynamics in the age of the dinosaurs

LIFE IN THE MESOZOIC

1 Apex predators

At the top of the Jurassic food chain were predators like Cryolophosaurus. Prowling through the forests that once flourished on the Antarctic continent, these reptiles had a taste for smaller predatory reptiles and herbivorous sauropods.

2 Giant herbivores

Sauropod dinosaurs, characterised by their giant bodies, long necks and small heads, were hunted by much smaller carnivorous theropod dinosaurs such as T rex and Cryolophosaurus.

3 Fish food

Prehistoric ray-finned fish known as laeonisciformes were not only prey to underwater predators, but were snatched from the surface by theropods.

4 The first furry meal

During the early Jurassic period, the first furry mammals emerged, known as Mammaliaformes. These rodent-like creatures were a great snack for energetic theropod hunters.

5 Predators eating predators

Smaller theropod dinosaurs such as Sarcosuchus were both hunted by larger theropods and hunters of herbivorous dinosaurs.

6 Variety meal

Carnivores at the lowest end of the food chain likely had more variety in the species they preyed upon, including other carnivores, herbivores and omnivores.

7 Plant-based

During the Jurassic period, herbivores feasted on ferns, conifers and ginkgos as the base-level producers of the food chain.

8 Tiny predators

The first mammal predators were likely insectivores, hunting beetles and scorpionflies.

Did you know?
Some paleontologists estimate that around 2.5 billion T rex lived and died between 66 and 68 million years ago

What was inside a dinosaur egg?

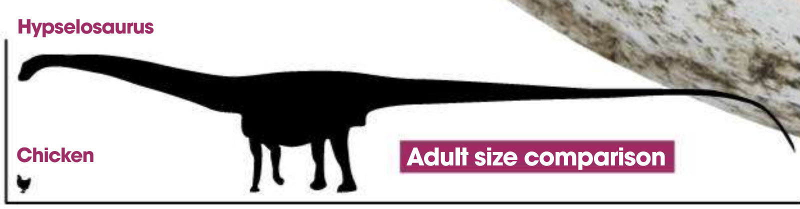
Just like modern–day baby chicks, dinosaurs grew and hatched from eggs to roam the planet a very long time ago

What came first – the dinosaur or the egg? We're not entirely sure, but what we do know is that these great reptiles laid eggs just like chickens do. Inside the shell of a hen's egg, chicks are able to grow before they're ready to hatch. That's just how the dinosaurs were born.

We know that baby dinosaurs were made this way because we have found lots of evidence. Fossilised dinosaur eggs have been found at over 200 sites across the world. They tell a story about how the dinosaur made its nest, laid its eggs and how baby dinosaurs were born.

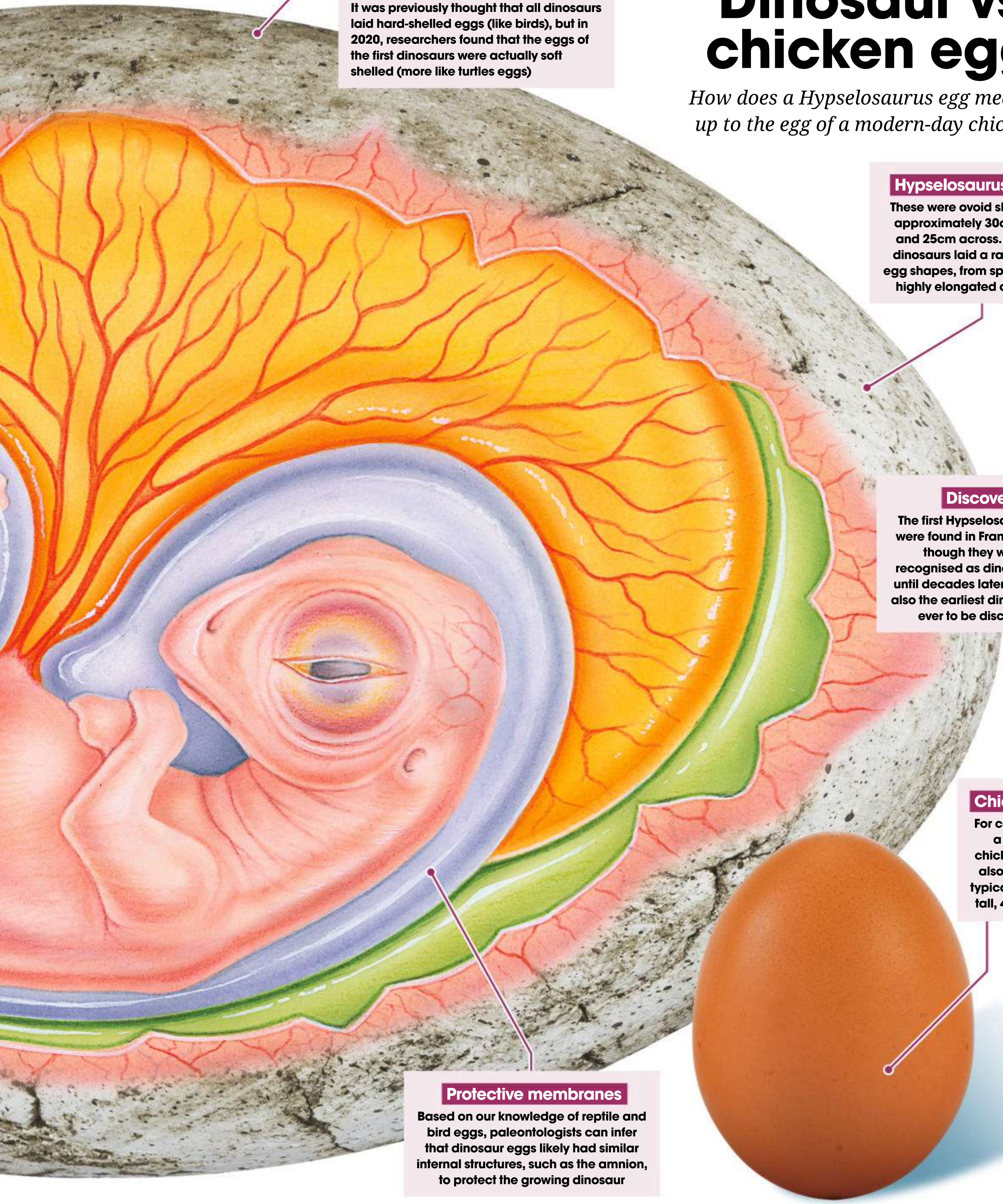
A crew of palaeontologists exploring Mongolia in 1923 were the first to scientifically recognise fossilised dinosaur eggs for what they were. Since then many dinosaur nesting sites for many different species have been uncovered all around the world. The oldest known dinosaur eggs and embryos date back to the Early Jurassic (about 190 million years ago) and come from the Massospondylus, a bipedal, omnivorous prosauropod.

Egg Mountain in Montana, US, is the site of one of the most famous dinosaur nest discoveries. Maiasaura remains were found near a nest with the remains of eggshells and babies too large to be hatchlings and this is the reason why Maiasaura is known as 'caring mother lizard'. Maiasaura and many other species of dinosaur, raised their young in nest colonies. This reflected the way that they herded when on the move. This amazing discovery was the first proof that dinosaurs raised and fed their young, rather than leaving hatchlings to fend for themselves like modern turtles do. Nests contained approximately 30-40 eggs and were not incubated by the parent sitting on them, but by the heat produced from rotting vegetation placed in the nest. It's thought that Maiasaura hatchlings left the nest after a year or two of rapid growth.



Dinosaur vs chicken egg

How does a Hypselosaurus egg measure up to the egg of a modern-day chicken?



Shell structure

It was previously thought that all dinosaurs laid hard-shelled eggs (like birds), but in 2020, researchers found that the eggs of the first dinosaurs were actually soft shelled (more like turtles eggs)

Hypselosaurus egg

These were ovoid shaped, approximately 30cm tall and 25cm across. Other dinosaurs laid a range of egg shapes, from spheres to highly elongated ovoids

Discovery

The first Hypselosaurus eggs were found in France in 1846, though they weren't recognised as dinosaur eggs until decades later. They were also the earliest dinosaur eggs ever to be discovered

Chicken egg

For comparison, a modern chicken's egg is also ovoid, but typically just 6cm tall, 4cm across

Protective membranes

Based on our knowledge of reptile and bird eggs, paleontologists can infer that dinosaur eggs likely had similar internal structures, such as the amnion, to protect the growing dinosaur

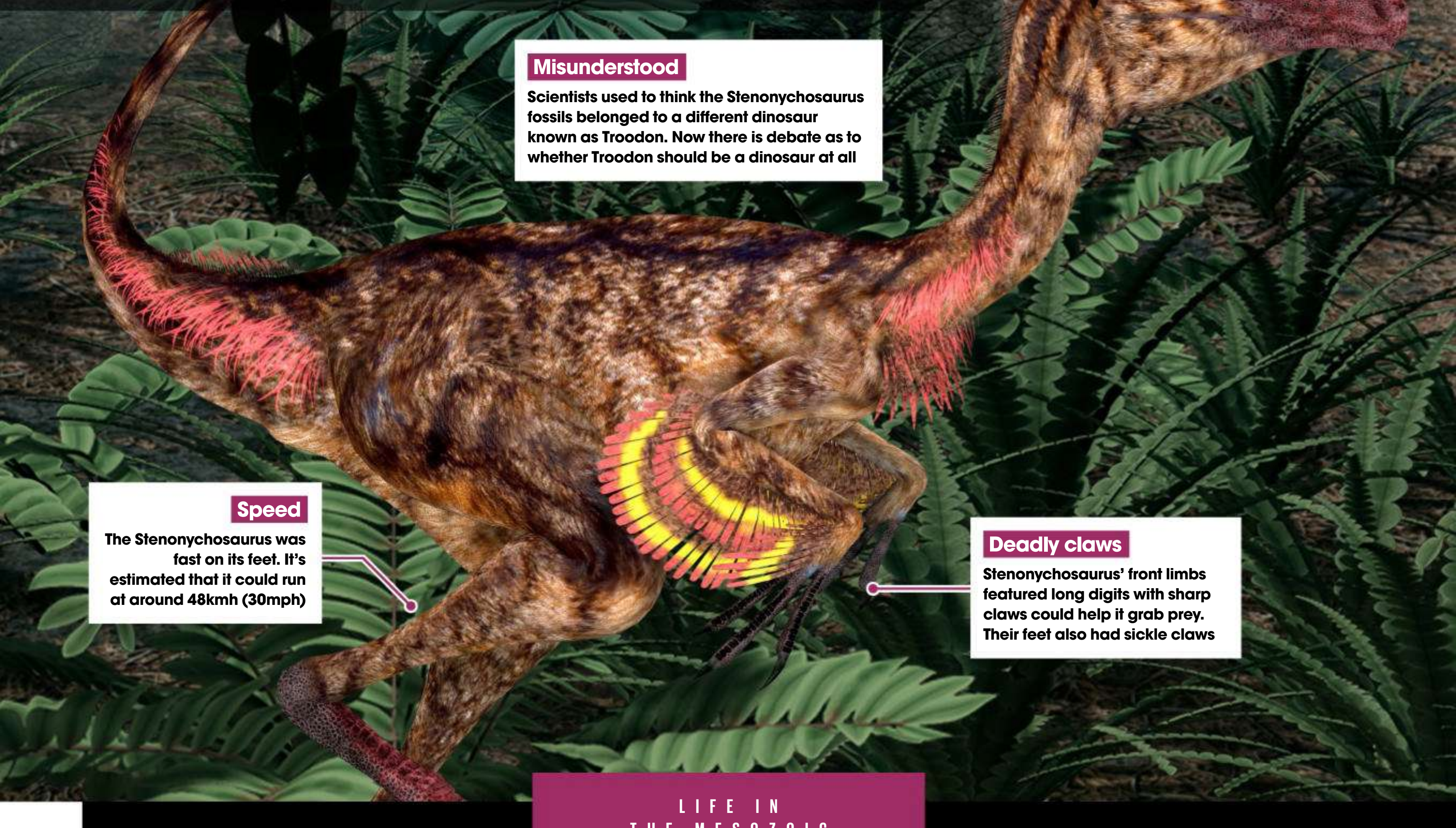
Which was the cleverest dinosaur?

The Stenonychosaurus was only about the same size as a human, but what it lacked in brawn it made up for in brains

Dinosaurs were not a brainy bunch, but the Stenonychosaurus was thought to be unusually smart. Relative to its size, its brain was much larger than those of other dinosaurs and evidence suggests that it was ferocious predator.

This bird-like dinosaur weighed about as much as a large dog, and it was very good at running, with its long legs and curved claws that would deliver the killer blow to prey. They were also clever enough to hunt in packs so they could catch much larger prey, but mostly hunted for small mammals, invertebrates and small reptiles. What's more, Stenonychosaurus's teeth were very sharp, and they had big eyes which likely gave them great night vision, so they weren't limited to hunting in daylight.

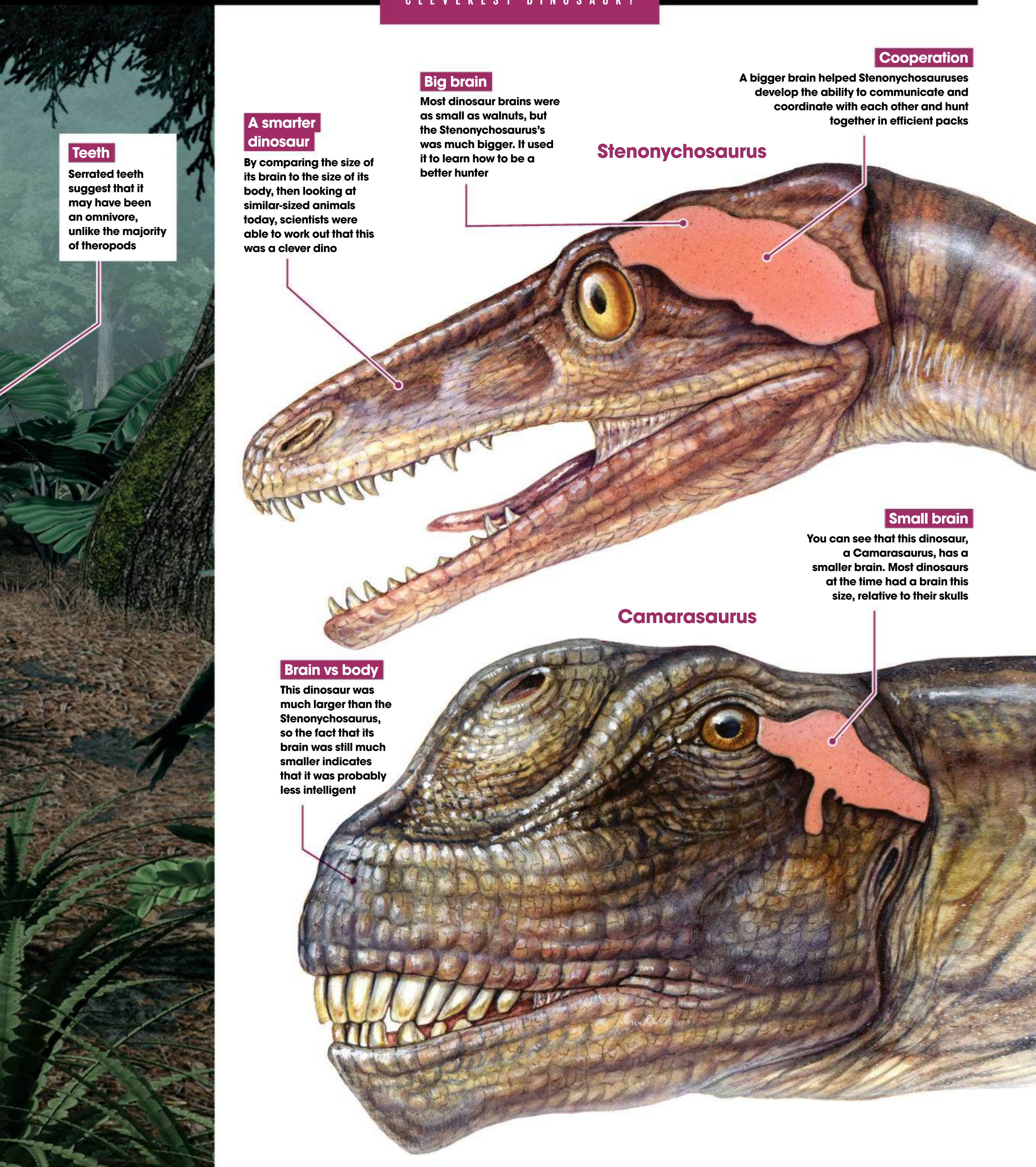
Did you know?
The name Stenonychosaurus actually means 'narrow claw lizard'

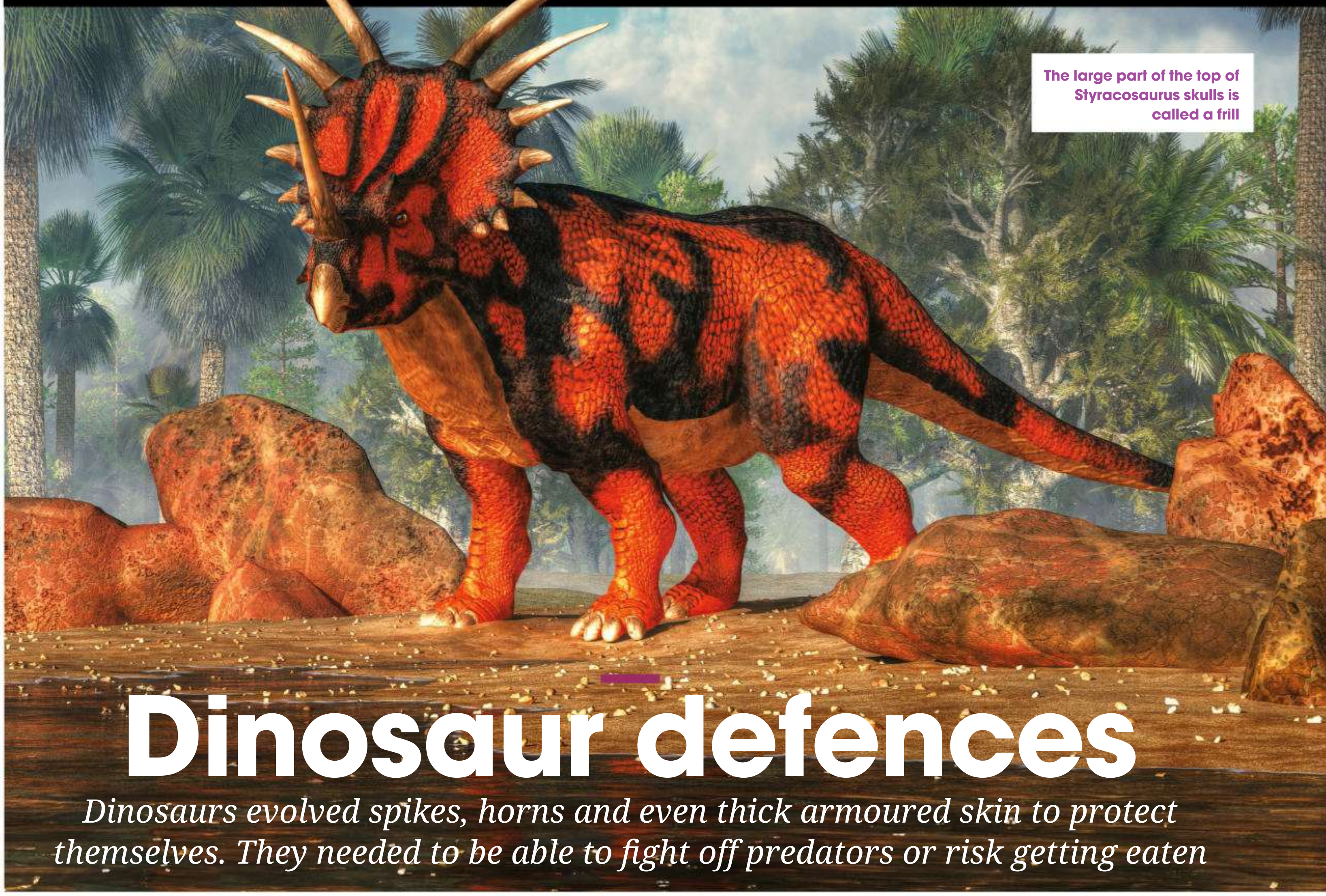


Misunderstood
Scientists used to think the Stenonychosaurus fossils belonged to a different dinosaur known as Troodon. Now there is debate as to whether Troodon should be a dinosaur at all

Speed
The Stenonychosaurus was fast on its feet. It's estimated that it could run at around 48kmh (30mph)

Deadly claws
Stenonychosaurus' front limbs featured long digits with sharp claws could help it grab prey. Their feet also had sickle claws


Teeth
Serrated teeth suggest that it may have been an omnivore, unlike the majority of theropods
A smarter dinosaur
By comparing the size of its brain to the size of its body, then looking at similar-sized animals today, scientists were able to work out that this was a clever dino
Big brain
Most dinosaur brains were as small as walnuts, but the Stenonychosaurus's was much bigger. It used it to learn how to be a better hunter
Cooperation
A bigger brain helped Stenonychosauruses develop the ability to communicate and coordinate with each other and hunt together in efficient packs
Stenonychosaurus
Small brain
You can see that this dinosaur, a Camarasaurus, has a smaller brain. Most dinosaurs at the time had a brain this size, relative to their skulls
Camarasaurus
Brain vs body
This dinosaur was much larger than the Stenonychosaurus, so the fact that its brain was still much smaller indicates that it was probably less intelligent



The large part of the top of Styracosaurus skulls is called a frill

Dinosaur defences

Dinosaurs evolved spikes, horns and even thick armoured skin to protect themselves. They needed to be able to fight off predators or risk getting eaten

Herbivorous dinosaurs developed built-in weapons to defend against carnivores. This gave them a better chance of surviving a fight against predators. It also gave them a better chance at defending vulnerable young against predation. Some dinosaurs had sharp claws on their hands, like Iguanodons, which could have been used as a tool and as a weapon. Dinosaurs like Triceratops had horns as long as a human arm that pointed forwards so that they could tackle enemies head on. Both these defences could have been used to stab attacking predators.

Other dinosaurs used their tails as weapons. The Ankylosaurus had a heavy, bony hammer at the end of its tail. They could use this to smash into an attacking dinosaur and they were strong enough to crush skulls and break bones. Some dinosaurs were covered in tough scales like a thick coat of armour. Stegosaurus had a row of bony plates running along its spine that are thought to be used for temperature control, though it's certainly possible that they were also used for defence. The bony plates ended along the tail but Stegosaurus remained well defended by the sharp spikes at the end of its tail. Powerful muscles could propel those spikes into an oncoming attacker. Indeed, Allosaurus remains have been found with wounds that line up perfectly with the dimensions of a Stegosaurus's tail spikes

Larger herbivores used their size as a defence. Dinosaurs like the Diplodocus were so massive that carnivores couldn't attack them easily. For smaller dinosaurs, running away was usually the best defence. They developed lighter bones so they could run faster. They needed to escape quickly to avoid fighting altogether.

Defensive features

Tail spikes

Tail spikes could be used as weapons because they were hard and sharp. They also made dinosaurs much harder to eat

Whip

Dinosaurs like Diplodocus had long tails that they could use like whips. It's possible that they snapped faster than the speed of sound

Tail club

Tail clubs were swung around just like a hammer. They were smashed into predators' legs and could crush bones

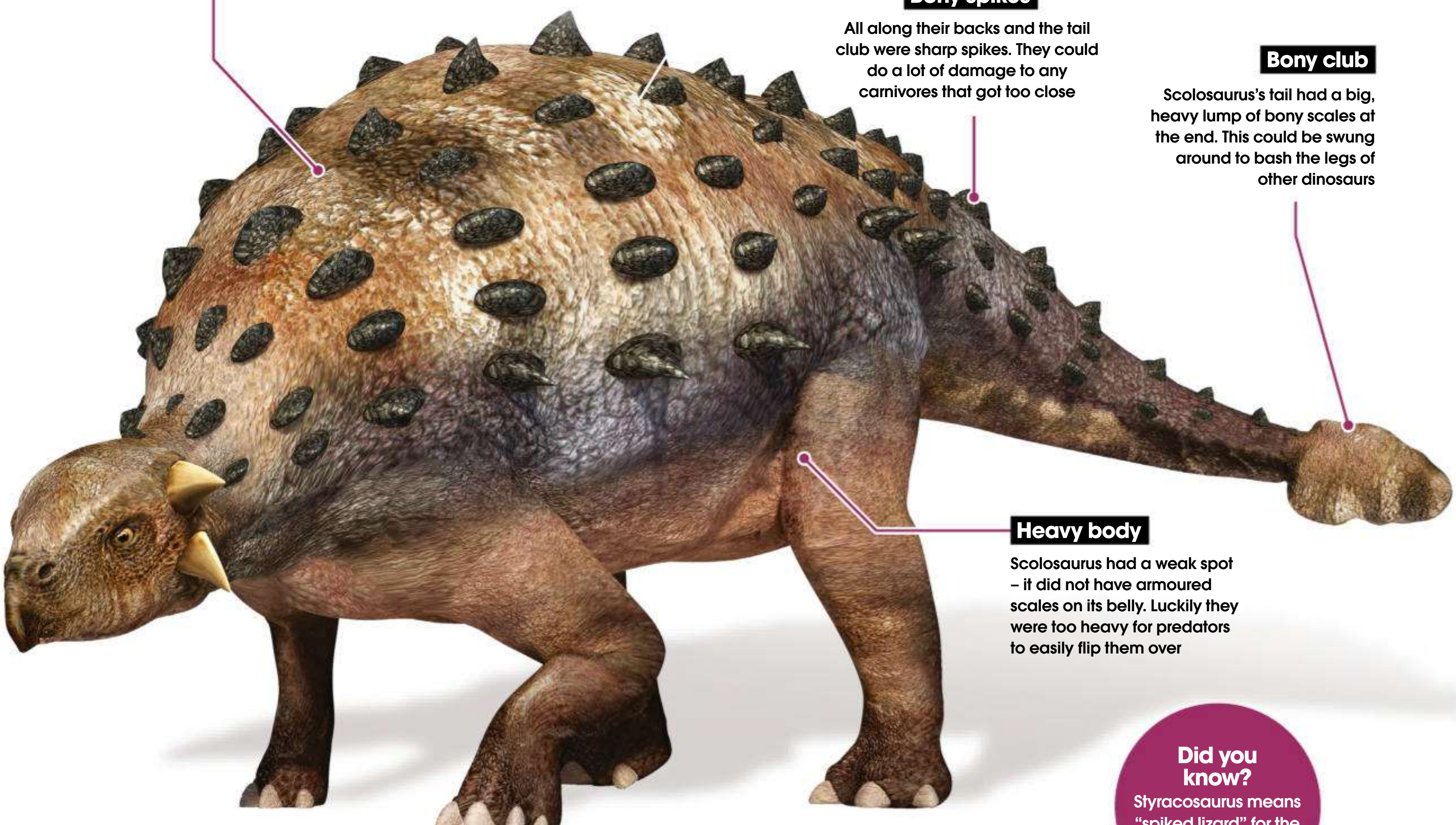
Horns

Horned dinosaurs might have charged towards predators to try and scare them away. Their horns could have ripped through skin

Armour plating

The Scolosaurus had a body built for defence - from a bony club at the end of its tail to thick scales covering its body

A Scolosaurus fossil at the National Museum of Nature and Science in Tokyo, Japan



Thick scales

Scolosaurus's bodies were covered in extra-thick scales that were as hard as bone. Predators would have had a tough time trying to take a bite out of them

Bony spikes

All along their backs and the tail club were sharp spikes. They could do a lot of damage to any carnivores that got too close

Bony club

Scolosaurus's tail had a big, heavy lump of bony scales at the end. This could be swung around to bash the legs of other dinosaurs

Heavy body

Scolosaurus had a weak spot – it did not have armoured scales on its belly. Luckily they were too heavy for predators to easily flip them over

Did you know?

Styracosaurus means "spiked lizard" for the large horns on its nose and frill

Crest

Head crests were used for communication. Dinosaurs could make warning calls to each other if they saw a predator nearby

Headbutt

Some dinosaurs, like Stegoceras, could smash skulls with predators. Their heads were protected by shock-absorbing layers of bone

"For smaller dinosaurs, running away was usually the best defence."

How do we know dinosaurs had feathers?

It turns out that fossils have preserved much more than just bone structure

Most of us have been captivated by the idea of dinosaurs since childhood. Among their numbers stood veracious hunters, towering leaf-eaters, armoured warriors and soaring giants. Add to that the wonder we all felt when we learned that our planet used to belong to them, that before we inherited the (self-awarded) title of Earth's apex animal, it was the reptilian dinosaurs that ruled supreme. In films, books and other illustrations we long envisaged dinosaurs to be clad in scales and thick skin, much like the reptiles of today – such as the terrifying yet magnificent Komodo dragon. A fearsome appearance such as this, after all, is only fitting for a world-conquering group. But would our perception of dinosaurs be altered if we were to learn that some were feathered and some were even fluffy?

Scientists found the first evidence of feathered dinosaurs over 150 years ago with the discovery of the Archaeopteryx. After the animal died, it left behind an immensely well-preserved fossil, and tucked beneath its long arms were the impressions of many familiar curved shapes. The evidence was clear for all to see – the Archaeopteryx had feathers. It wasn't until the 1990s, however, that scientists would uncover much more evidence that showed that Archaeopteryx wasn't alone in its feathery ways. Archaeologists in China unearthed a collection of complete fossils that had a clear halo of 'dino fuzz' surrounding the skeletal impressions, which they determined must had been a form of primitive feathers, or fur.

The modern expert opinion holds that an entire group of dinosaurs, known as the Theropods, likely bore feathers in some capacity. These would have started as fluffy, primitive barbs, but in some species would have evolved into fully established feathered wings that were sometimes used for flying. Perhaps most intriguingly, the beloved velociraptor and the T rex belong to this group. So these terrifying creatures may have looked much more 'cuddly' than was previously believed.

The colour mystery solved

We may now know that many dinosaurs were adorned with some sort of feathered coat, but what colours were they? If we look to today's avian descendants of the dinosaurs, birds, we see a spectrum of coloured plumage used to perform a bunch of different functions, such as camouflage and attracting a mate. But with limited insight into a dinosaur species' behaviour, we can only make an educated guess as to how these factors could have contributed to their feather colour.

Fortunately, precious fossil evidence lends us concrete proof of the colours worn by dinosaurs, for some colours at least. Using sophisticated microscopes, in well-preserved fossils we can identify impressions of pigment molecules that have been preserved for tens of millions of years.

These pigments have well-defined shapes that are responsible for particular colours, which enable scientists to determine if a dinosaur's feathers bore this hue. We can also compare the structures of these ancient pigments against modern-day birds, allowing us to unlock the secrets of the past by using the present.

Feathered family tree

Theropod feathers evolved to help dinosaurs in a variety of ways, from disguise to flight

Filament

Protofeathers were composed of single hollow filaments. These would later evolve into established feathers in many species.

Tuft

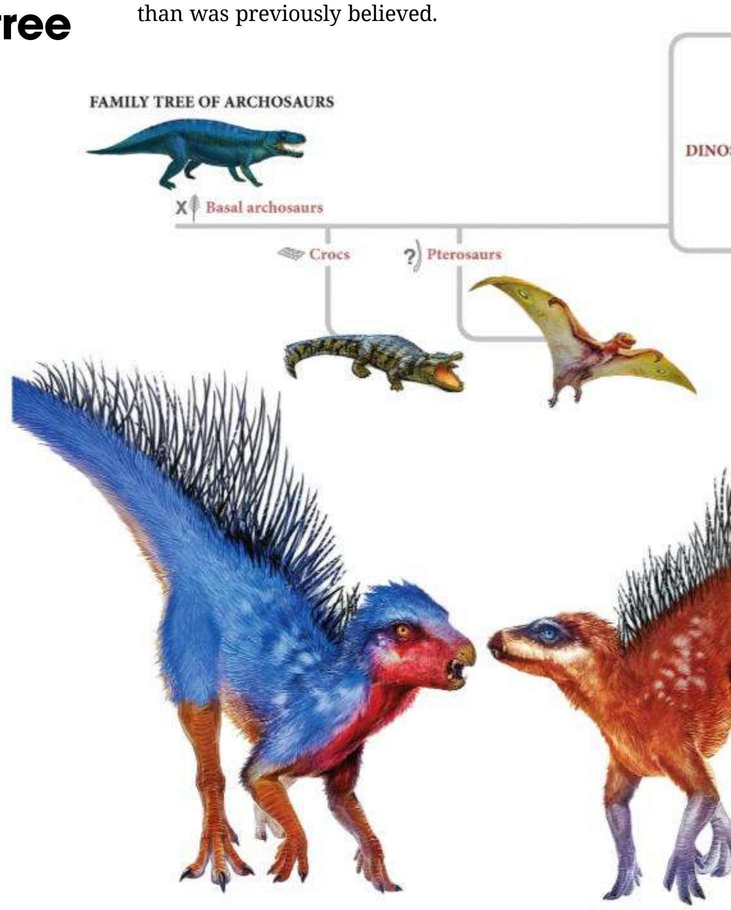
Protofeathers evolved into tufts of several filaments, giving dinosaurs a halo of fluff either in patches or a full coat.

Barbs

Over many generations tufts would have transformed into more rigid and organised structures of barbs connected to a central shaft.

Feather

Eventually, barbs would have been crosslinked by structures known as barbules, producing advanced feathers capable of supporting full flight.

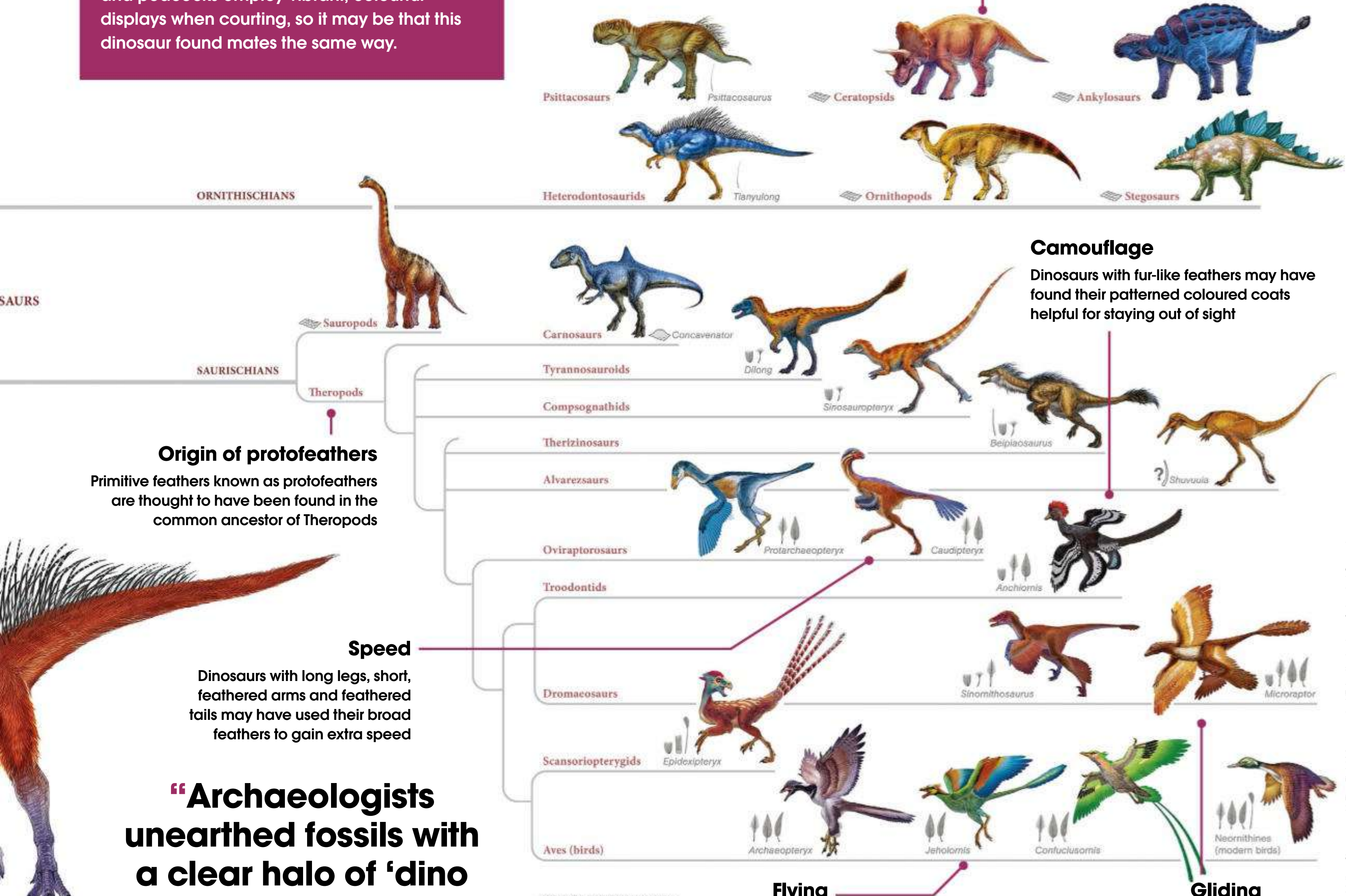


The rainbow dino duck

A duck-sized dinosaur that had the basic shape of a bird and the snout of a raptor likely lit up the forests of the Mesozoic era with its flashy displays. Named as Caihong juji, or 'rainbow with the big crest', the prehistoric animal's fossilised remains were found with brilliantly preserved feathers that had retained fragments of pigment sacs known as melanosomes. The shape and orientation of these sacs is most similar to those of iridescent hummingbird feathers, meaning that Caihong juji likely had a plumage that vibrantly shone in the colours of the rainbow. We can only speculate as to its purpose, but hummingbirds and peacocks employ vibrant, colourful displays when courting, so it may be that this dinosaur found mates the same way.

The Caihong juji was discovered to have similar feather pigmentation to colourful hummingbirds

Modern reptiles such as the Komodo dragon inspired us to think that all dinosaurs were scaled, not feathered



Scaled

Many dinosaurs outside of the Theropod branch would have been mostly scaled and sometimes clad in thick armour

Camouflage

Dinosaurs with fur-like feathers may have found their patterned coloured coats helpful for staying out of sight

Origin of protofeathers

Primitive feathers known as protofeathers are thought to have been found in the common ancestor of Theropods

Speed

Dinosaurs with long legs, short, feathered arms and feathered tails may have used their broad feathers to gain extra speed

"Archaeologists unearthed fossils with a clear halo of 'dino fuzz' surrounding the skeletal impressions"

Flying

Member species with large, feathered arms likely took to the skies and used their long tail to help steer

Gliding

Some Theropods had feathered legs as well as feathered arms and tails, which meant they probably used the added air resistance for gliding

What did dinosaurs sound like?

Despite what you see on TV and in the movies, dinosaur calls may have been more about hissing and hooting than roaring and screaming

Thanks to Hollywood blockbusters, our view of the prehistoric world is certainly a loud one. From shrieking pterosaurs in the sky to a cacophony of roars, hisses and screams on land, we've come to accept a world rich with the sounds of dinosaur life.

Of course, speculation forms a significant part of our understanding of the prehistoric world, but how many of our preconceptions are the product of dramatic licence, as well as the false assignation of modern animal characteristics to these ancient creatures? Thankfully, experts in the field of palaeontology are helping to uncover the truth behind the misconceptions - and the reality they've unearthed might have been a lot quieter than the movies suggest.

Twin lineages

The fossilised remains of dinosaurs have helped paleontologists and other scientists craft an intimate understanding of their physiology, but the nature of their communication is a facet that still eludes us. So what facts do we have to work with?

We know that dinosaurs, birds and crocodiles all belong to a reptilian group called the Archosauria, a group which contains all the extinct species of dinosaur as well as all the extinct members of the crocodilian family. Archosaurs were fast becoming the most common creatures in the late Paleozoic and early Mesozoic eras, and during the Triassic period (around 250 to 200 million years ago) this family diverged into two separate genetic clades: the Pseudosuchia (which includes crocodilians and their ancestors) and the Avemetatarsalia (which is home to birds, all non-avian dinosaurs and pterosaurs).

"Crocodiles and birds both vocalise, so it's tempting to infer that they inherited vocalisation from a common ancestor," says Dr Phil Senter, an associate professor of Biology at Fayetteville State University, North Carolina. "So this should mean that all

Five dinosaurs most likely to vocalise

The hadrosaurids had all the right genetic tools to make a racket

1 Parasaurolophus
+ Parasaurolophus (the name means 'near-crested lizard'), was a herbivorous ornithopod that roamed what would become North America in the Late Cretaceous epoch. It had one of the most recognisable cranial crests, with a long tube that stretched behind its head.

2 Saurolophus
+ Saurolophus ('lizard crest') belonged to a genus of large hadrosaurids that existed 69.5 to 68.5 million years ago in the Late Cretaceous epoch. Its remains have been found in North American and parts of Asia. It had a spike-like crest that extends backwards from its cranium.

3 Olorotitan
+ Olorotitan was a genus of 'duck-bill', or lambeosaurine hadrosaurid, that lived in the Late Cretaceous epoch. It may have grown up to 12 metres long and had an unusual crest that stretched back above its head in a fan-like shape.

4 Edmontosaurus
+ Edmontosaurus was discovered back in the 1920s in the Horseshoe Canyon Formation in Alberta, Canada – although its remains were initially misclassified to another genus. Like many hadrosaurids, it lived in the Late Cretaceous epoch.

5 Gryposaurus
Existing 83 to 75.5 million years ago during the Late Cretaceous epoch, Gryposaurus was a genus of duck-billed dinosaur whose remains have been found right across Canada and the US. Unlike many hadrosaurids from this period, Gryposaurus was distinguished not by a cranial crest, but by its enlarged nasal passages.

"Crocodiles and birds both vocalise, so it's tempting to infer that they inherited vocalisation from a common ancestor"
Dr Phil Senter, Fayetteville State University

Words: Dom Reseigh-Lincoln. Image: Getty images

Research suggests that larger dinosaurs likely made low-frequency and infrasonic sounds, beyond the limits of human hearing

extinct archosaurs probably vocalised as well. However, in this case, we should resist temptation. That's because the vocal cords of crocodilians are not homologous with those of birds, so the two developed them independently, rather than both inheriting them from a common ancestor.

"We know this is the case because they're on different structures," Senter continues. "Crocodilian vocal cords are in the larynx, while the bird larynx has no vocal cords. Instead, bird vocal cords are in the syrinx, an organ that is unique to birds."

Bird calls

So if dinosaurs originate from the bird line of divergence, would they share similar vocal characteristics with their feathery relatives? From what evidence we have already, it seems highly unlikely.

The syrinx requires a component known as a clavicular air sac in order to function. If this air sac is punctured, a bird is no longer able to produce sound. The expansion of this sac leaves a mark on the humerus, sternum or clavicle, which serves as a opening from which it can extend.

The most primitive birds from the Mesozoic period lack any such marks, as do their dinosaur relatives the Coelurosaurs (a family of dinos that includes troodontids, oviraptorids, tyrannosaurids and dromaeosaurids). Interestingly, one dinosaur has been discovered with such a marking: the Aerosteon. This 2.7m-long Argentinian carnivore was non-avian, so it likely gained this sac independently as well.

The earliest known birds that have this bony mark can be found in the Early Cretaceous epoch, with examples including the group called enantiornithes and the genus Sapeornis. By contrast, Archaeopteryx and Jeholornis, two genera of avians from the Mesozoic era, show no trace of this mark, despite forming the foundation of the bird family tree. "It's possible that some dinos gained vocal cords independently of birds, but we have no direct evidence for this," continues Dr Senter. "The nasal passages within the crests of some hadrosaurs (duck-billed dinos) resonate at low frequencies and could have amplified low-frequency sounds. However, this does not necessarily mean that they had vocal cords. King cobras and certain other snakes have soft-tissue resonating chambers that amplify certain frequencies, so that the snake's hiss sounds like a growl. We cannot discount the possibility that crested hadrosaurs were doing something similar."

All of these theories are quite convincing, so why has popular culture represented these beasts of the prehistoric era as being loud and vocal creatures? Dr Senter has a pragmatic take on this common misconception. "My take on things will no doubt disappoint fans of roaring T rexes and honking duckbills in movies," he

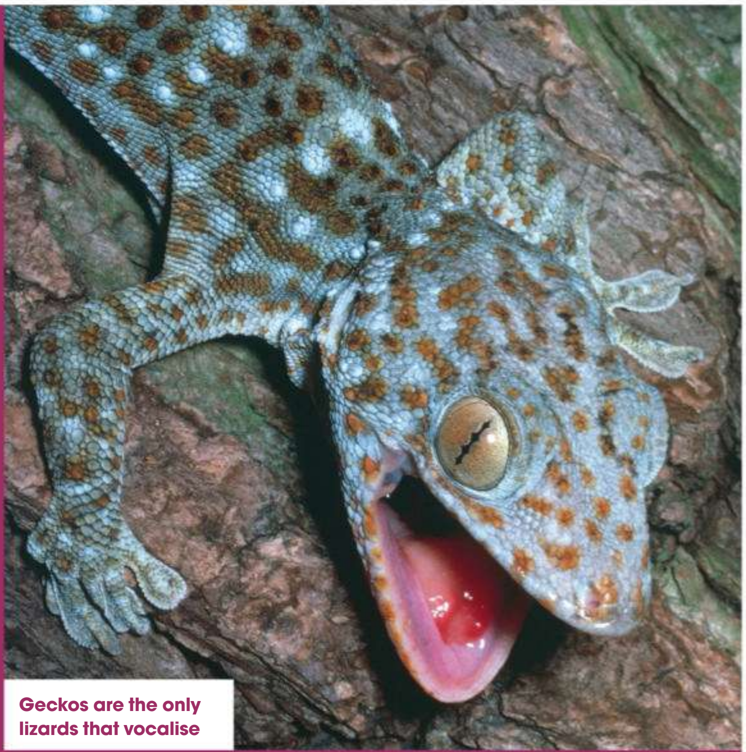
Q&A Dr Thomas Williamson

Curator of Palaeontology at the New Mexico Museum Of Natural History And Science

Research has shown us that hadrosaurs used specialised crests to communicate with another. Could you explain how this communication worked?
The portion of a hadrosaur's respiratory tract between its nostrils and its posterior internal nares forms long, curved airways and at least one chamber within its crest. Such air-filled volumes will resonate at low frequencies. It is not known if hadrosaurs had a vocal organ analogous to the human larynx, but the crest may have been excited to produce sounds in other ways.

Modern lizards are quiet creatures, while birds are often quite loud. What might this tell us about dinosaur vocalisation?
Geckos are the only lizards that vocalise. But the closest living relatives of hadrosaurs – the crocodilians and birds – are both capable of making sounds which they use to communicate with others of their own species. This ability is undoubtedly related to their possession of sophisticated social behaviour.

Would some dinosaurs have used non-vocal communication instead of sound?
Without a doubt, dinosaurs would have used visual communication. Distinctive and bizarre cranial structures are widespread among many types of dinosaurs, for instance. This kind of head ornamentation developed as the animals neared sexual maturity, and is thought to have functioned in species recognition.



Geckos are the only lizards that vocalise

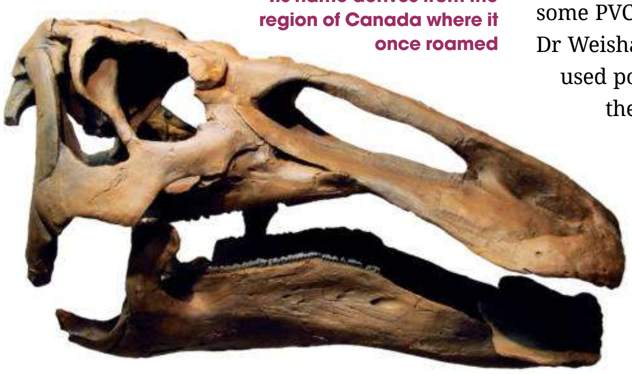
"The closest living relatives of hadrosaurs, crocodilians and birds, are both capable of making sounds"

Dr Thomas Williamson, New Mexico Museum of Natural History and Science

says, "but movie magic is mostly made-up for entertainment's sake and not for accuracy's sake. It's more likely that dinosaurs, like most of today's reptiles, hissed when disturbed but could not vocalise. They were probably silent the rest of the time.

"This, however, makes them even more frightening as movie villains," he continues. "Isn't it much scarier to have a silent predator sneaking up on you than a squealing goofball who gives away his location?"

The skull of an Edmontosaurus. Its name derives from the region of Canada where it once roamed



Simulating sound

Over the years, scientists and paleontologists have made numerous attempts to recreate the possible sounds and calls of a dinosaur. One particular study, conducted in 1996, remains one of the most intriguing in fleshing out our understanding of how the dinosaurs might have sounded.

It took its inspiration from a previous 15-year experiment led by Dr David B Weishampel - an American palaeontologist now working at Johns Hopkins University School of Medicine - who constructed a Parasaurolophus crest from some PVC tubing and a trumpet mouthpiece. Dr Weishampel proposed that this creature used powerful, low-pitched sounds similar to the ultra-low sounds used by elephants today. So years later, when Dr Robert Sullivan and Dr Tom Williamson discovered a new Parasaurolophus fossil in New Mexico, the two palaeontologists were contacted by three scientists from the Sandia National Laboratories in Albuquerque, who wanted to use a new scanning technique to recreate the skull of this ancient herbivore.

Due to the pressure of the rock formations they're found in, Parasaurolophus skeletons are usually semi-compressed, destroying the true size, shape and density of the remains. But using the only partly compressed skull unearthed by Sullivan and Williamson, the Sandia scientists were able to use stereolithography, a form of laser scanning, to recreate a physical version of it in plastic.

"The basic frequency of the note is set by the length of the tube," says one of the three scientists involved, Dr Carl Diegert. "But we're interested in much more than that. We're trying to refine the work done in the 1980s by Dr Weishampel. For instance, we want to know not only what the sustained sound of the animal might have been, but also what its acoustic attack might have been like - the start of the animal's call, like the attack of a trombonist as he begins to play."

Were dinosaurs warm-blooded?

We tend to think of them as cold-blooded and sluggish, but mounting evidence suggests dinosaurs had an edge over their reptile cousins

When the giant bones that researchers kept unearthing were properly categorised and identified as a unique group of animals by Richard Owen in 1841, their apparent similarity to modern day reptiles was reflected in the name 'dinosaur' – Greek for 'terrible lizard'. For a long time they were thought of as slow, stupid animals which died out because they were unable to compete with faster, more agile creatures, such as mammals. In the 1860s, English biologist Thomas Huxley was the first to suggest that these lumbering beasts could have been the ancestors to modern birds. But birds are agile, elegant, warm-blooded animals, not clumsy, cold-blooded swamp dwellers, so the idea didn't stick.

The theory resurfaced in the 1960s when Yale University's John Ostrom studied the Deinonychus and saw a fast, agile hunter, built for speed. He revived the idea of a link between dinosaurs and birds, and postulated that dinosaurs could have been warm-blooded.

One famous piece of evidence in favour of dinosaurs being cold-blooded are the 'lines of arrested growth', or 'lag', which appear during bone formation, in a similar way to tree rings. They happen when growth is slowed or stopped whenever environmental conditions aren't favourable and energy is rerouted to keep the creature alive. Such lines are visible on modern day cold-blooded animals, and since dinosaurs possessed them too, the argument was that dinosaurs were cold-blooded.

However, it seems no one did a sufficiently thorough study of other animals. In June 2012, Nature published the findings of a team at the Catalan Institute of Palaeontology, who had analysed the thigh bones of mammals from all over the world. Until then it was assumed that, being warm-blooded and therefore better shielded from irregular weather conditions, mammals would grow bones in a continuous

Did you know?
Endotherms are animals that generate their own body heat, like birds, whereas ectotherms rely on the environment to regulate their body temperature, like reptiles

Five arguments for dinosaurs being cold-blooded

The case for the traditional, ectothermic view of dinosaurs considered

1 Inertial homeothermy
Dinosaurs were quite large and so didn't need to be warm-blooded to keep a constant temperature. A phenomenon called 'inertial homeothermy' could allow them to warm up and cool down slowly. However, not all dinosaurs were large ones – and even the large dinosaurs started small as infants.

2 Warmer climate
The climate was much warmer and wetter back then so dinosaurs didn't need to be warm-blooded to keep warm. But this doesn't explain how dinosaur fossils were found in the polar regions. How could cold-blooded dinosaurs have survived there?

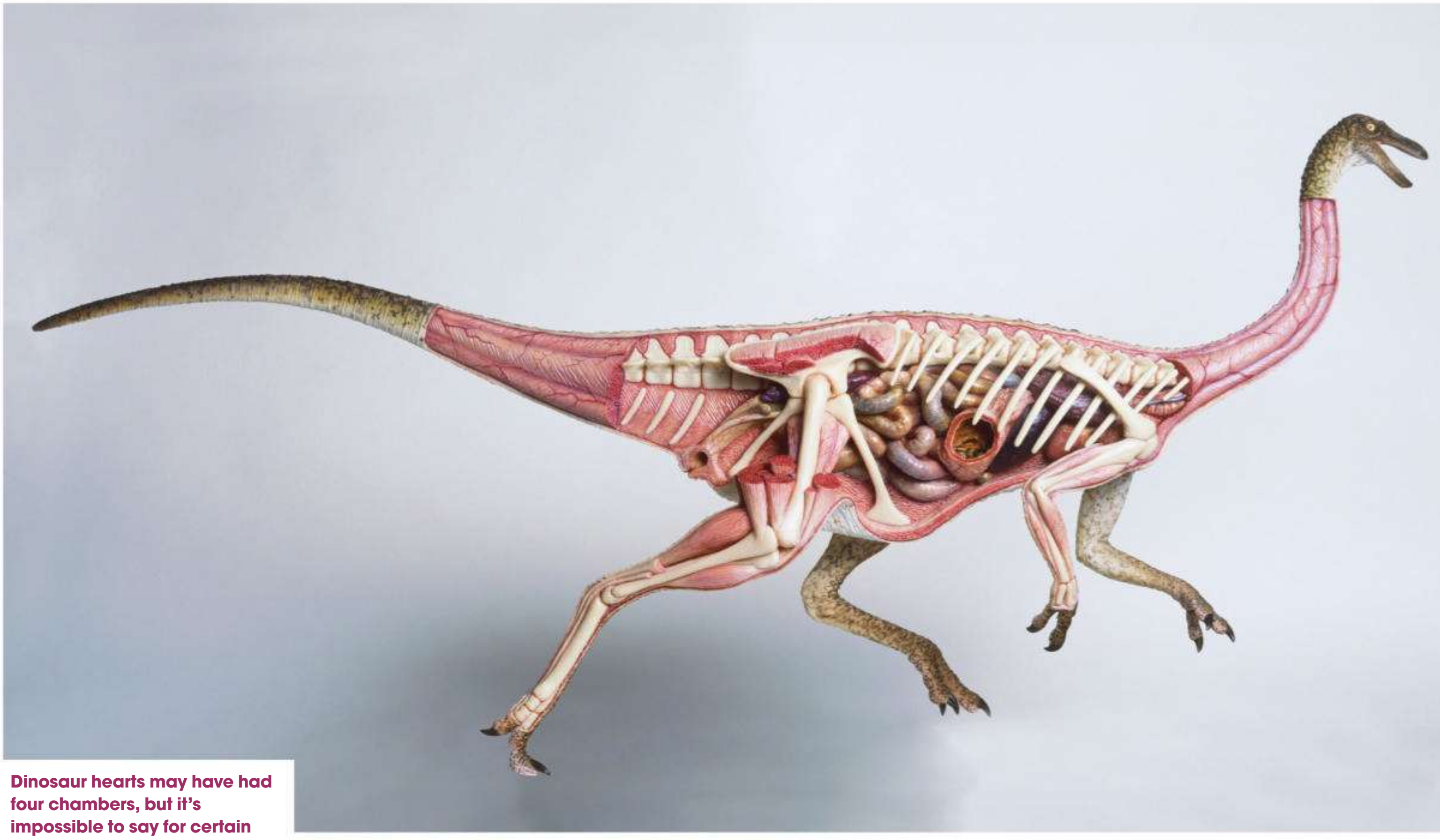
3 Scales
Modern cold-blooded animals are generally scaly, and fossilised dinosaur skin impressions show the appearance of scales. But birds are scaly too, and it is believed that feathers are in fact modified scales. Also, feathered dinosaurs have now been uncovered.

4 Sauropod necks
If the large sauropods didn't elevate their long necks but kept them horizontal, there would be less need for high blood pressure for the blood to reach their brain and so less need for them to be warm-blooded.

5 Respiratory turbinates
Modern birds and mammals have structures in their nasal passages called 'respiratory turbinates', which are essential for the maintenance of high lung ventilation rates and endothermy. So far, such turbinates haven't been found in dinosaur fossils.

"In the 1960s, Yale's John Ostrom postulated that dinosaurs could have been warm-blooded"

Words: Steve Paris. Image: Getty Images



Dinosaur hearts may have had four chambers, but it's impossible to say for certain

fashion until adult size was reached. But that assumption turned out to be completely wrong: the team found lines of arrested growth in all the mammals they studied. This means lags cannot be used as proof that dinosaurs were cold-blooded.

Another piece of evidence in favour of dinosaurs being cold-blooded is the crocodile. Just like dinosaurs, it's a member of the archosaurs group, and although it's not a direct dinosaur descendant, they are still closely related. Since the crocodile is cold-blooded, the argument goes, so must dinosaurs have been. But nothing is as simple as it seems.

Professor Roger Seymour from the University of Adelaide is no stranger to studying dinosaurs to look for clues to their warm-bloodedness. Back in 1976, he published an article in Nature titled Dinosaurs, Endothermy and Blood Pressure, in which he concluded that not only would sauropods have needed high blood pressure to get blood up to their long necks, but that a four-chambered heart similar to that found in mammals or birds would have been necessary to regulate the flow of blood between the heart and the lungs (which needs to be at a low pressure so as not to drown the animal in its own blood) and the rest of the body. This lends credence to the theory that dinosaurs would have been warm-blooded.

Modern-day crocodiles hold clues as to whether dinosaurs were warm-blooded or not

He recently did extensive research on the crocodile, and believes his findings add further weight to the idea that all archosaurs were warm-blooded. "I argue that the living crocs gave up endothermy at some point and became ectotherms because of a sit-and-wait behaviour," he confirms. "Yet they still had a four-chambered heart, as testament to their warm-blooded ancestry. No other reptile has a four-chambered heart. The birds and crocodiles are the only living descendants of the early archosaurs."

There's a major advantage to being warm-blooded. "[It gives you] the ability to move quickly and continuously," explains Seymour. "Cold-bloods quickly fatigue and would lose a battle [with faster creatures like mammals]."

That's because of the different pathways the two types of animal use to transform energy into power. Cold-blooded animals mostly use anaerobic pathways which produce lactic acid as a by-product. Warm-blooded animals also use aerobic pathways, leading to the production of heat and CO_2, neither of which remain in the body. Due to the build-up of lactic acid, anaerobic pathways aren't sustainable over long periods of time. Professor Seymour showed that, at peak exercise, a 200kg crocodile can only produce around 14% of the muscular power of a mammal of similar size. The larger the animal, the lower that fraction got. In other words, being cold-blooded would have made those giant dinosaurs pretty lethargic, and extremely vulnerable to predators.

Another piece of evidence came from research Seymour conducted in 2011 on the blood supply to bone. Our thigh bones, for instance, have tiny holes known as 'nutrient foramen' which is where blood is supplied to sustain the bone. He theorised that the more active the animal, the more blood would be needed to maintain the bone in peak

Q&A Professor Roger Seymour

Why the evidence for warm-blooded dinosaurs has this evolutionary biologist convinced

How did you get interested in dinosaur physiology?
I've been interested in dinosaurs all of my life. However, I research the comparative physiology of living animals and merely apply those concepts to dinosaurs.

The notion of warm-blooded dinosaurs has been around since the late 19th Century. Why is the idea more popular now?
There are many lines of evidence now. The most important include feathers, the link between high blood pressure and being warm-blooded, and the dominance of dinosaurs over mammals.

What are the biggest clues you have that dinosaurs weren't cold-blooded like reptiles?
My contribution was the link between high blood pressure and warm-bloodedness. Birds and mammals have high blood pressure to support a high metabolic rate. We know that some dinosaurs must have had high blood pressure, simply because they were so tall. So it makes sense that the dinosaurs were warm-blooded, and that their high blood pressure allowed them to become tall.

Warm-blooded animals eat more. Wouldn't warm-blooded dinosaurs have a serious impact on their environment?
No more so than the large terrestrial mammals that followed them. The population of large endotherms involved would have been relatively small.

Dinosaurs laid eggs, and some had feathers – did they also, perhaps, share birds' endothermy?

"We know that some dinosaurs must have had high blood pressure, simply because they were so tall"

Professor Roger Seymour, University of Adelaide

physical shape. In order to prove his theory, he compared the size of those holes from the bones of many animals, both mammals and reptiles, and checked if there was a link with the animal's physical activity.

The results showed conclusively that the more active the animal is, the larger those holes are. In fact, the holes found in mammals are ten times larger than those found in reptiles. Taking this research further, Seymour then analysed the fossilised bones of ten dinosaur species and discovered something startling – their nutrient foramen were even bigger than those found in mammals. The conclusion is obvious: those giants had a very high metabolic rate, higher still than that of mammals living today.

Getting warmer...

Taking all this information into account certainly makes it feel like the case for warm-blooded dinosaurs is getting stronger with each new discovery. However, could there have been a mixture of cold and warm-blooded dinosaurs? Not according to Professor Seymour. "It is unlikely that two strategies could exist together on equal footing," he says. "Cold-bloods today need defences other than simple power in order to survive. Also, you don't find large cold-bloods in the cool climates that existed near the poles during the Mesozoic era."

Making a case for dinosaurs being warm-blooded does lend more weight to the theory that birds are their descendants. "Yes," confirms Professor Seymour. "Birds have the four-chambered hearts necessary to separate the high blood pressure going to the body from the low blood pressure going to the lungs." All living archosaurs were warm-blooded at some point in their evolution, so the odds are high that dinosaurs were too.

Unless some drastic new theory comes to light that casts doubt on all of this research, it looks as though dinosaurs were indeed highly active, powerful, warm-blooded giants that ruled the world for millions of years – and would most likely have kept on doing so, had it not been for our planet's unfortunate encounter with an extremely large meteorite 65 million years ago.

With very little soft tissue preserved in fossils, reconstructing dinosaur biology is no easy task

Did dinosaurs migrate?

The search for food may have led huge dinosaurs to travel huge distances in order to sate their appetites

Herbivorous dinosaurs, or sauropods, were the largest animals ever to walk the Earth. They were long-necked, massive creatures with huge limbs, and a fine skeletal example greets you every time you enter the Natural History Museum in London. On average, they were around 23 metres long and weighed 20 tons. Some scientists speculate that these dinosaurs got so big because their teeth weren't designed to chew. This means they would have had to swallow their food pretty much whole, and in order to process the ingested matter and get enough energy from it, their stomach got bigger, which led to ever larger sauropods. Interestingly, these very same teeth also reveal some different, yet surprising secrets about these animals' behaviour.

Where sauropods roam

It stands to reason that one such creature would put a serious strain on the local plant life, so a herd would devastate an area in a very short amount of time. Over the years, many scientists have theorised that just like birds, or large mammals such as elephants, these dinosaurs may have migrated from one area to another in search of greener pastures, and to give the land they just left a chance to recover. But how can solid evidence for this be found, when the species in question have been extinct for millions of years?

That's where Professor Henry Fricke of Colorado College comes in. His team drew on their expertise of geology to bring tools

Did you know?
The name 'sauropod' means 'lizard foot' Like almost all dinosaur names and classifications, the name derives from Greek

Five facts about the Camarasaurus

What you need to know about this common North American sauropod

1 Discovery
The Camarasaurus was discovered by in 1877 Edward Drinker Cope, who during his lifetime discovered, described and named more than 1,000 vertebrate species, including fish and dinosaurs. According to Mark Jaffe he was "perhaps the brashest, most creative, and quixotic palaeontologist of the 19th Century".

2 Hollow bones
Camarasaurus was the most common of the giant sauropods in North America. It existed between 155 and 145 million years ago and its name means "vaulted chamber lizard", which refers to the hollow chambers in its vertebrae.

3 Bulging spine
Camarasaurus' neck and tail are shorter than other sauropods of its size, but like other members of its family it has an enlargement of the spinal cord near its hips. This was originally thought to be a second brain, as the cavity was larger than its actual brain, but the idea has since been ruled out as this type of enlargement has been found in many other vertebrate animals.

4 Strong legs
Camarasaurus had thick legs, obviously to cope with its massive size, and five-toed feet. Its front legs were marginally shorter than its back ones, and its front inner toes, which were larger than the others, had a long sharp claw, most likely used for protection.

5 Superfluous stones
Stones have been found in the stomach cavities of Camarasaurus fossils. It was thought they swallowed stones to aid in digestion, as some bird species do today, but now it's believed the stones were ingested accidentally.

to bear that palaeontologists usually aren't able to, or don't consider. In this case, that involved focusing on oxygen-18 isotopes, which are heavier atoms than regular oxygen, being possessed of two additional neutrons. Focusing on sauropod herds that lived in what is now North America, specifically those of the genus Camarasaurus, the team found that water and plants in lower-altitude regions contained high levels of oxygen-18 isotopes, whereas those from the highlands were poorer in oxygen-18.

In addition to this, as Professor Fricke explains, "Dinosaurs replaced their teeth regularly throughout their lives, like crocodiles and sharks, with each tooth forming over a period of a few months". So the nutrients they consumed would be used in the creation of new teeth. This means that a diet of plants and water rich in oxygen-18 would lead to the creation of oxygen-18-rich enamel layers as their teeth developed, giving a great window into what the dinosaur was eating during the tooth's lifetime.

And that's where a puzzle was uncovered. The teeth fossils they analysed were from the Dinosaur National Monument in Utah and Thermopolis in Wyoming, and came from dinosaur remains found in a low-altitude region. Most of those teeth were quite worn and retained only a month or two of enamel growth, but some allowed Fricke's team to analyse up to five months' worth of enamel.

Those teeth's isotope levels didn't match those of their surrounding area, which meant that wherever the sauropods were when

Words: Steve Paris. Image: Getty Images

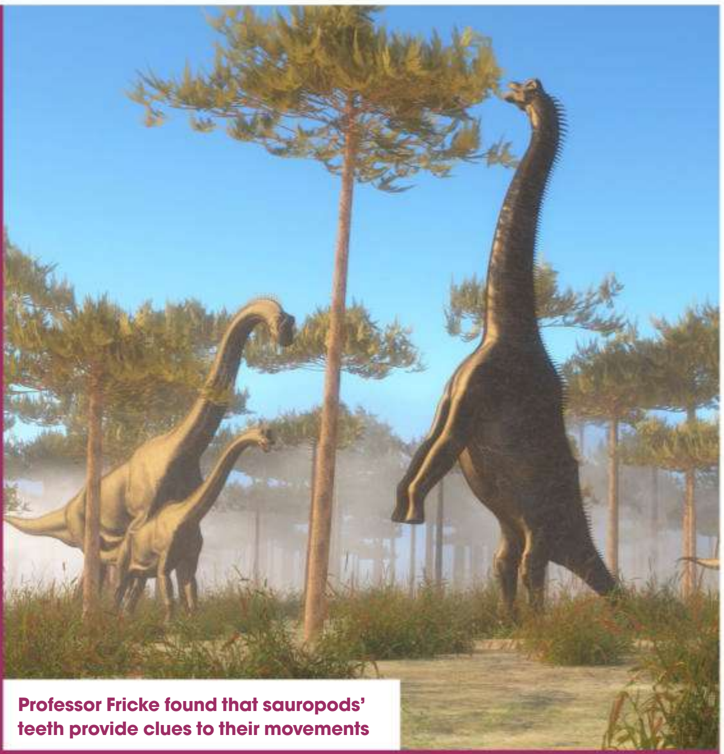
Q&A Professor Henry Fricke

How a professor of geology came to be researching dinosaur migration

As a professor of geology, how did you get interested in dinosaur physiology?
I've long had a tendency to follow unusual research directions. In the case of dinosaurs, an opportunity arose when I ran into a college friend at a meeting who invited me to do some fossil collecting with him in Montana one summer. Sitting around the fire talking with him, I realised there were a bunch of unanswered questions out there that I could study. I've been hooked on dinosaurs ever since.

What evidence suggested to you that dinosaurs migrated?
The palaeontologists did the heavy academic lifting. Based on studies of modern analogues as well as the study of fossils, it's long been hypothesised that large dinosaurs could have migrated. My goal was to bring geochemical tools to bear to try and test this hypothesis – tools not typically utilised by palaeontologists.

How did you find the evidence of migration?
We initially collected chemical data from sauropod teeth with the goal of studying dietary niche partitioning - that is, whether one type of long-necked dinosaur was eating something different from another. When we first got the data back I couldn't make sense of it, because it didn't match up with the local rocks. This got us thinking about other explanations of the data, such as migration. So in this case I'd say we stumbled across the answer!



Professor Fricke found that sauropods' teeth provide clues to their movements

"I realised there were a bunch of unanswered questions out there. I've been hooked on dinosaurs ever since"
Professor Henry Fricke, Colorado College

A Camarasaurus fossil from Dinosaur National Monument, Utah

"The study showed that sauropods migrated great distances during their lifetimes"

they were growing those teeth, wasn't where they ended up dying. Based on the team's knowledge of geology, they believe those Camarasaurus spent at least some time in the highlands, around 300km away.

Not all animals who died in the same area showed the same level of oxygen-18 in their teeth, but that's hardly surprising since they wouldn't have died at the same time. Sadly, no dinosaur fossils have been found in the highlands so it isn't possible to make a comparative study, but this again was expected since erosion typically washes any evidence away from the highlands.

Nonetheless, the fact that these teeth contained a different level of oxygen-18 than the surrounding area is the first conclusive


Dinosaurs may have migrated in large herds, just as many herbivorous mammals do today

proof that large dinosaurs migrated in search of food.

Why migrate?

Considering the effort required to undertake such journeys, why would these large herbivores feel the need to move around, instead of simply remaining in one place? "Migration could have been driven by environmental conditions in western North America during the Jurassic period," explains Professor Fricke. "There may have been seasonal drying in low-elevation areas, driving a move to wetter, high-elevation areas. Access to a continuous supply of plant material to feed these big animals would also be part of the equation. Lastly, such large animals might have been migrating simply because they had evolved to do so efficiently. It's much easier for an animal with three-metre legs to walk 100km than it is for something that's smaller!"

So did all herbivorous dinosaurs migrate? "We won't know until we study them all!" laughs Professor Fricke. "If I had to hazard a guess, though, I would say that migration would be limited to big animals living in drier environments, much as it is for mammals today."

Then and now, herds of herbivores would inevitably attract predators. But were the dinosaurs that preyed on the Camarasaurus region-specific, or did they follow the herd as they moved from the lowlands to the highlands?

"This is a great question," says Professor Fricke. "To know for sure we will have to undertake chemical studies of these animals as well as herbivores. In the case of the Jurassic period we have preliminary data from theropod fossils that have been found in association with the sauropods, and it does look like the predators were following the sauropods."

This study was groundbreaking, showing that sauropods migrated great distances during their lifetimes, but it's not enough to determine whether this behaviour was seasonal or whether these animals had a more nomadic lifestyle. "It is hard to answer this question," admits Professor Fricke, "because we get our information from dinosaur teeth, but these teeth only give us a small window into dinosaur behaviour. So we can only study the last bit of their travel history, rather than longer-term patterns."

Tracking through time

It must have been quite a sight to behold: herds of 20-ton creatures moving hundreds of kilometres from one area to another, grazing on tree leaves and shrubs as they went (grasses hadn't yet evolved, or at least they hadn't for most of the sauropods' reign on Earth), and possibly being followed by predators, hoping for an opportunity to strike. Imagine watching lions tracking wildebeest across the Serengeti, but on a monster scale. Not that any humans would've been around to see it of course – but our distant mammalian ancestors were there in the background, waiting for their turn in the spotlight.

What's even more remarkable, though, is that unbeknown to them, their diet over time and in different locations would lay down the clues necessary to confirm their migratory habits, all thanks to the thin layers of dental enamel they produced over the course of their lifetimes.

Dinosaurs in Focus

Tyrannosaurus rex

Learn about the lizard king's physiology and how it presided over the prehistoric jungle

The Tyrannosaurus rex was a species of Theropoda dinosaur in the Late Cretaceous period. Like other tyrannosaurids – such as the Tarbosaurus and Gorgosaurus – the T rex was a bipedal carnivore and apex predator and scavenger, preying on smaller dinosaurs directly or out-muscling them for their kills. Typical prey included Hadrosaurs and Ceratopsians.

The Tyrannosaurus rex's name translates as 'tyrant lizard king', something that was historically attributed due to its immense size. Indeed, the Tyrannosaurus rex is one of the largest species ever excavated by palaeontologists, with specimens averaging over 12 metres in length and four metres in height, but it wasn't the biggest carnivorous dino. It was also incredibly heavy, with fully grown adults weighing up to nine tons; this figure was suggested in 2011 after an in-depth study that made digital 3D models of five T rex skeletons.

Due to its considerable size the Tyrannosaurus rex had very few, if any, predators, a fact that enabled it to remain unchallenged as the Late Cretaceous era's apex predator on land and to live for lengthy periods. Estimates taken from excavated specimens, of which there are now more than 30 confirmed around the world, indicate that the T rex's lifespan was roughly 30 years, with the majority of growth taking place in the first 16 years before tailing off rapidly. This suggests that the Tyrannosaurus rex would have reached adulthood at approximately 20 years of age.

As with almost all species of dinosaur, the Tyrannosaurus rex was wiped out 65.5 million years ago in the Cretaceous-Palaeogene (K-Pg) extinction event. At the time it was one of the last widespread non-avian dinosaurs, as evidenced by the discovery of many specimens throughout North America.

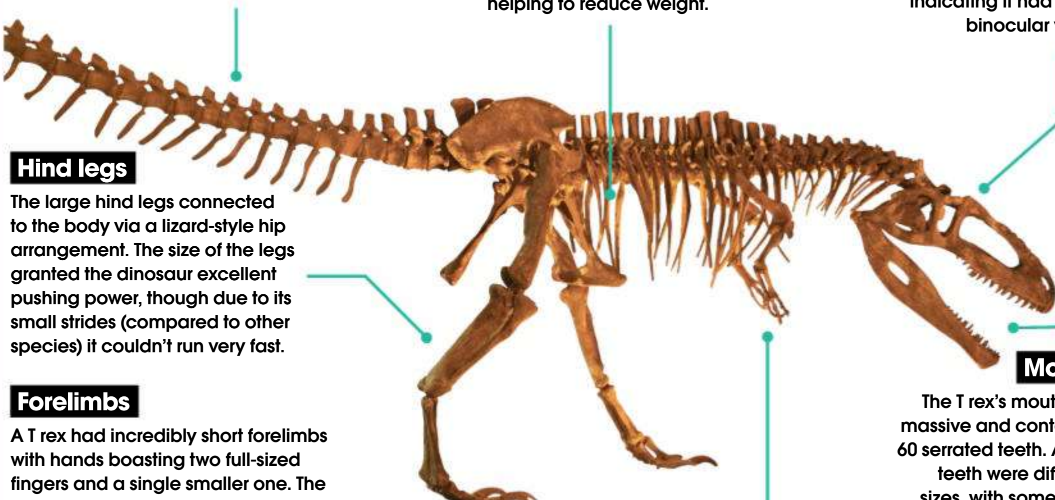
Movie mythbusting

Due to a variety of films depicting the T rex in their own unique way, an accurate view of the species has been clouded. Despite being a prominent star of the Jurassic Park films, the Tyrannosaurus rex did not exist in the Jurassic period (199-145 MYA). In fact, it lived millions of years later during the Late Cretaceous (100-65.5 MYA).

Further, for decades the T rex has been depicted as having green scaly skin. However, recent evidence suggests its skin colour was varied and, during the early years of its life, it probably sported insulative feathers. The T rex has also been commonly lauded as the biggest carnivorous dinosaur of them all. This isn't strictly true, with palaeontological evidence suggesting the species Spinosaurus outsized it by over three metres in length.

And finally, another myth perpetuated in *Jurassic Park* is that the Tyrannosaurus rex could run at high speed (able to keep up with a car), but it could probably only manage approximately 40 kilometres per hour due to its relatively small strides.

Lizard king anatomy



Tail

Crucial for maintaining balance – especially as modern evidence suggests the T rex had a near-horizontal spinal position – the dinosaur's large tail was essential for chasing prey.

Body cavity

The Tyrannosaurus rex had an incredibly heavy body structure and a wide body cavity. To improve mobility, some of the dinosaur's vertebrae had holes, helping to reduce weight.

Skull

A Tyrannosaurus' skull was huge and its snout and lower jaw were very deep. The eye sockets faced forward to a greater degree than most dinosaurs, indicating it had acute binocular vision.

Hind legs

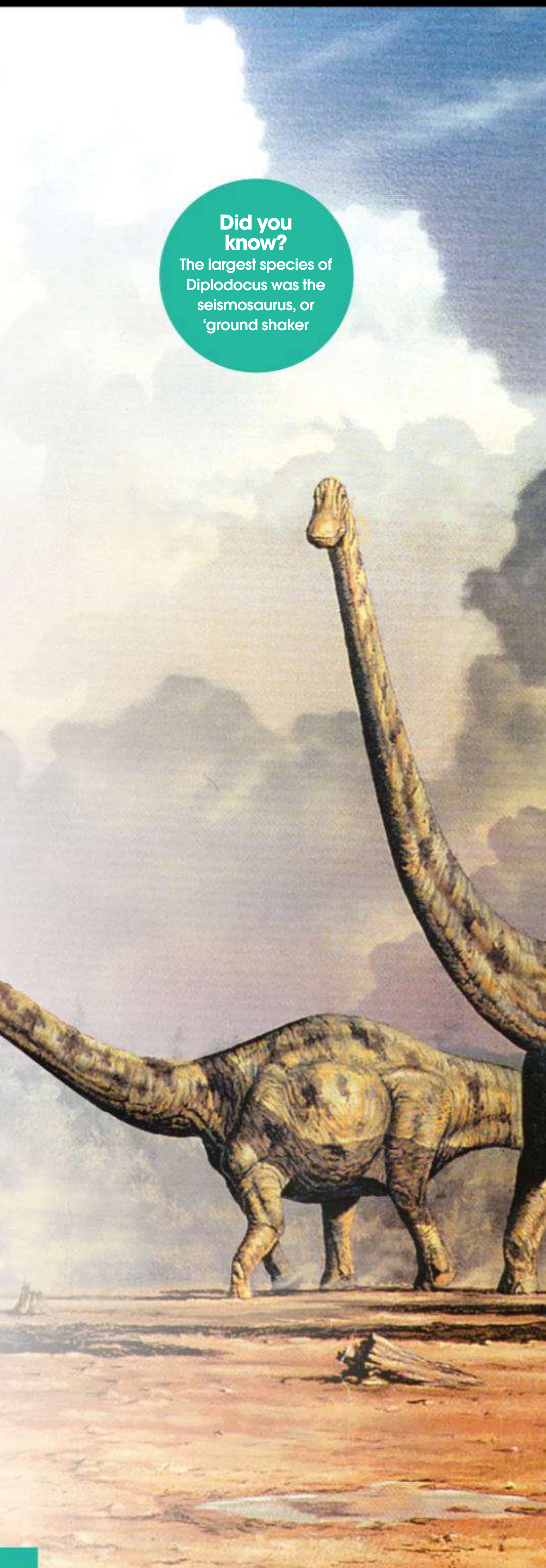
The large hind legs connected to the body via a lizard-style hip arrangement. The size of the legs granted the dinosaur excellent pushing power, though due to its small strides (compared to other species) it couldn't run very fast.

Forelimbs

A T rex had incredibly short forelimbs with hands boasting two full-sized fingers and a single smaller one. The two larger fingers were equipped with razor-sharp, sickle-shaped claws.

Mouth

The T rex's mouth was massive and contained 60 serrated teeth. All the teeth were different sizes, with some up to 20cm long.



Diplodocus

We find out how this mighty dinosaur once lived

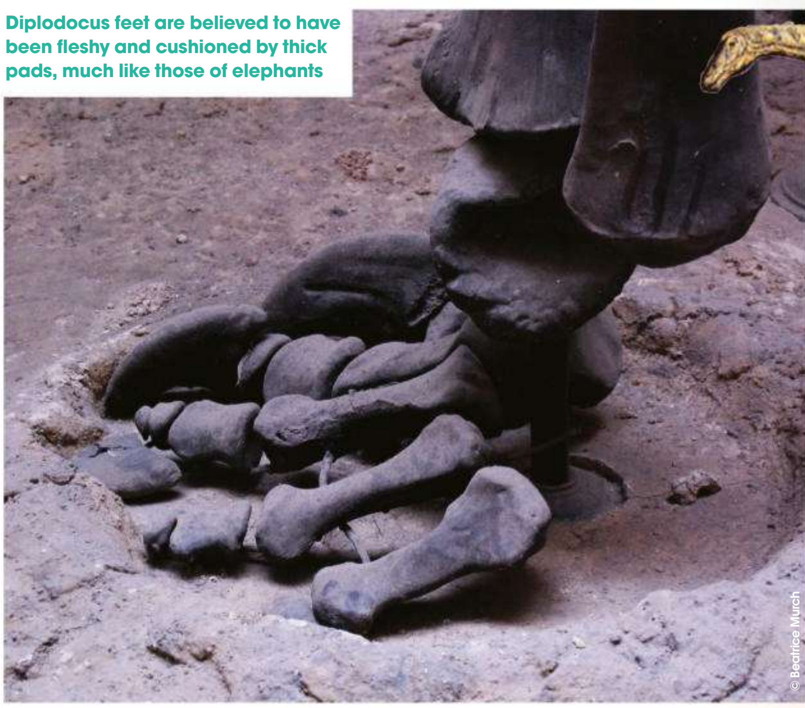
Did you know?
The largest species of Diplodocus was the seismosaurus, or 'ground shaker

The Diplodocus is, without doubt, one of the most famous dinosaurs. It belonged to the group known as the sauropodomorphs and lived during the Late Jurassic period — specifically the Kimmeridgian and Tithonian eras roughly 154-150 million years ago. It reached sizes of up to 25 metres in length and was predominantly found in what is now North America. There were four species of Diplodocus, with the largest of these being the Seismosaurus, which essentially translates as 'ground shaker'.

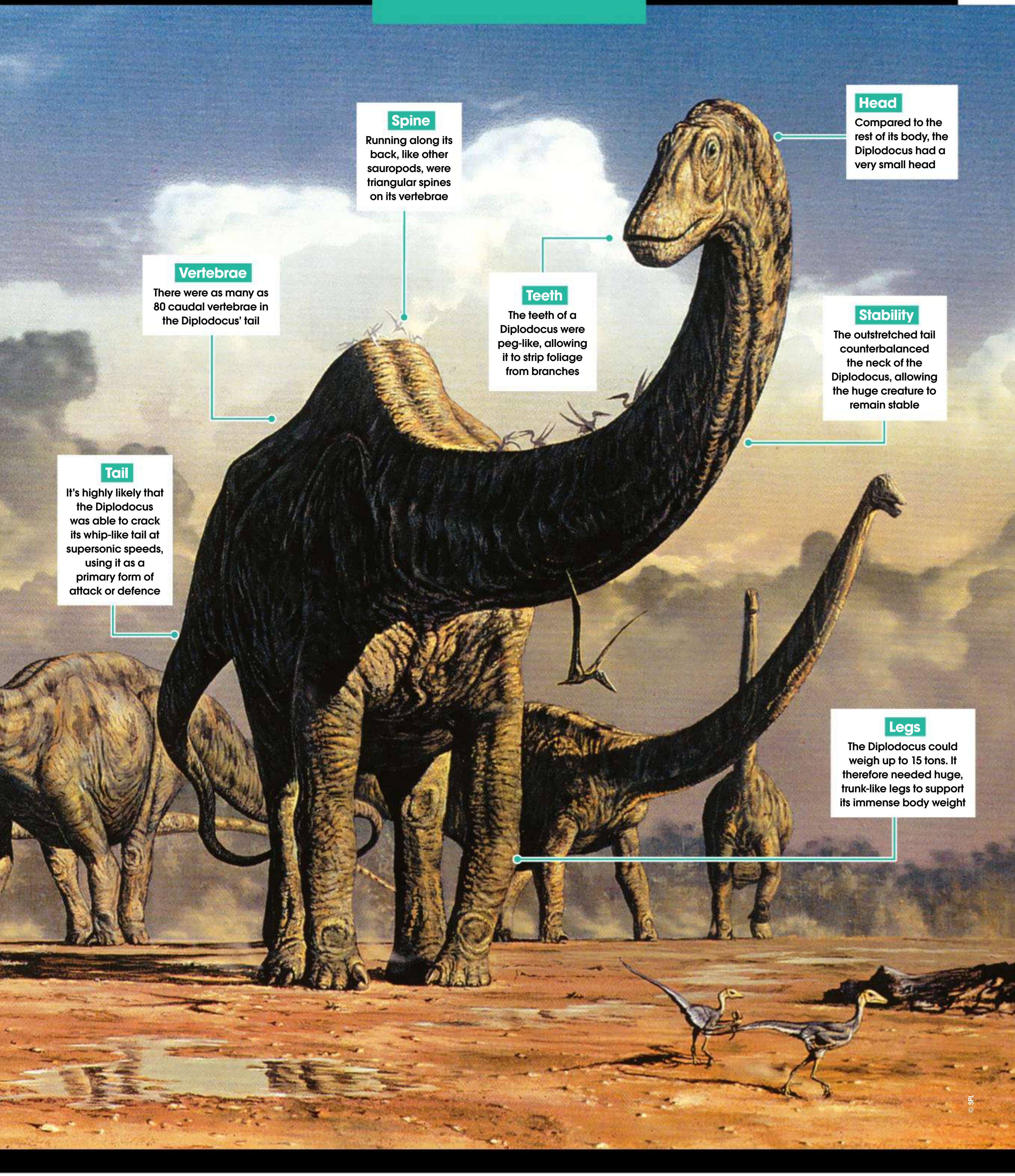
Part of the Diplodocid family, it shared the same characteristic of having 15 neck vertebrae, short forelimbs compared to the rest of its body and a whip-like tail. Its giant neck made up a large proportion of its body, but there is still some contention as to whether it held its neck vertically or horizontally. Its rectangular skull contained huge eye sockets and nasal chambers in addition to a long flat jawline and a small space for its comparatively little brain.

Studies of its teeth suggest that the Diplodocus fed using a method known as branch stripping, where the branch of a tree is grasped in a creature's jaw and then pulled sharply up or down, tearing off foliage as it goes.

For its time, the Diplodocus was the largest dinosaur around. While it was later eclipsed by other sauropods, it roamed the tallest for at least a few million years. Numerous Diplodocus bones have been found and studied by palaeontologists, providing an insight into how these giant dinosaurs were able to support themselves, and revealing clues as to how they lived.



Diplodocus feet are believed to have been fleshy and cushioned by thick pads, much like those of elephants


Head
Compared to the rest of its body, the Diplodocus had a very small head
Spine
Running along its back, like other sauropods, were triangular spines on its vertebrae
Vertebrae
There were as many as 80 caudal vertebrae in the Diplodocus' tail
Teeth
The teeth of a Diplodocus were peg-like, allowing it to strip foliage from branches
Stability
The outstretched tail counterbalanced the neck of the Diplodocus, allowing the huge creature to remain stable
Tail
It's highly likely that the Diplodocus was able to crack its whip-like tail at supersonic speeds, using it as a primary form of attack or defence
Legs
The Diplodocus could weigh up to 15 tons. It therefore needed huge, trunk-like legs to support its immense body weight
© SPL

Parasaurolophus

These herbivores had some very distinctive headgear

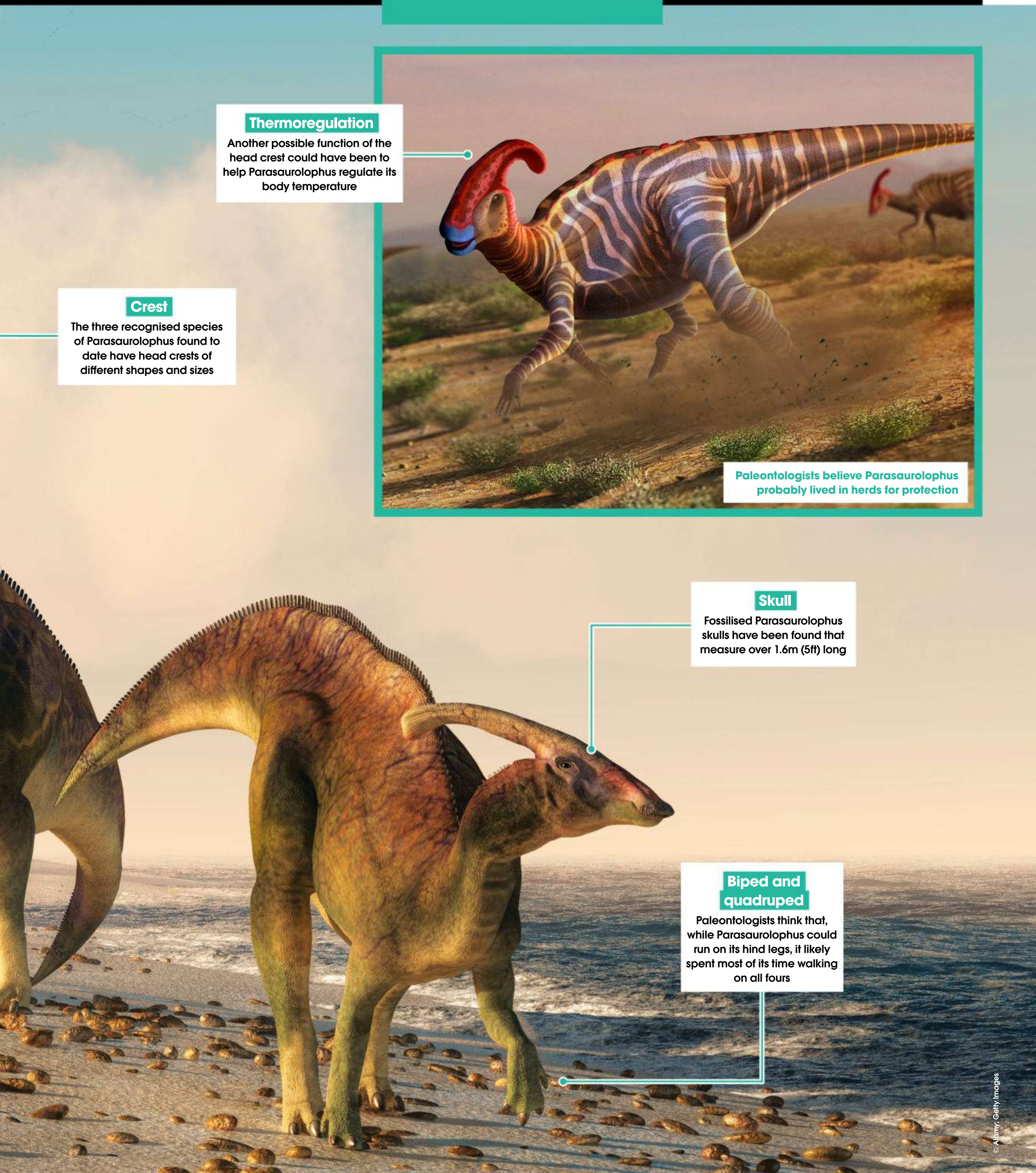
This 11-metre (36-foot)-long herbivore grazed on the plains and in the forests of North America 75 million years ago. It wasn't outrageously fast or particularly big (for a hadrosaur), and it didn't have an impressive club tail or spiky thagomizer with which to wallop predators. However, it did have something to boast of: a built-in trumpet.

The Parasaurolophus had a distinctive, hollow crest on top of its head, which acted like a resonating chamber. Paleontologists believe that it was most likely used for communication, such as when a herd member needed to alert the others of danger, would turn its call for alarm into a loud, horn-like honk that would be impossible to ignore. This striking-looking noisemaker may also have been used for mating calls and for mothers and children to locate each other.

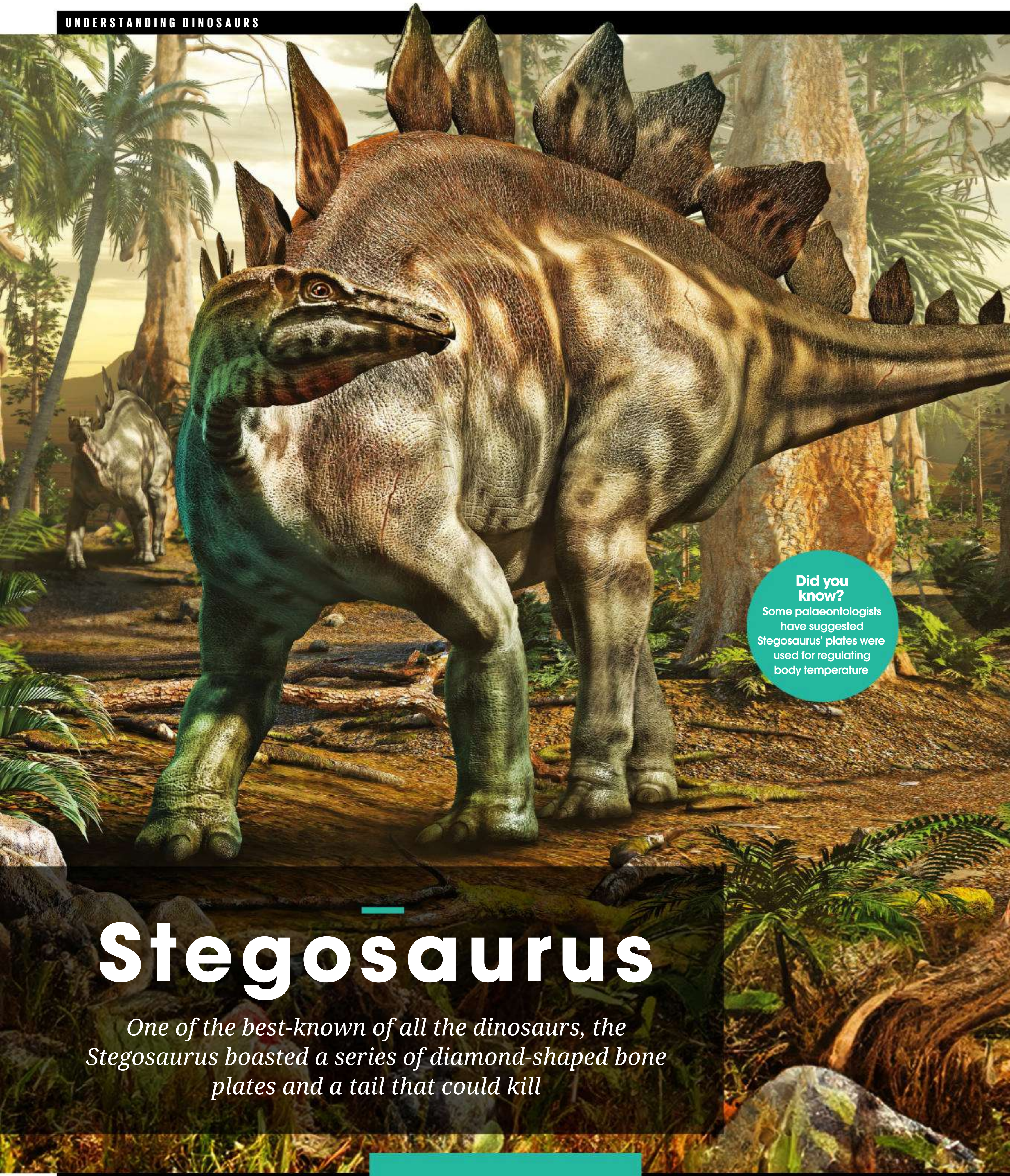
By analysing the skull airways of a well-preserved Parasaurophus skull, scientists used computer modelling to try and replicate the sounds they might have made. The results are an eerie trombone-like hum.

Grinding Teeth

The Parasaurolophus' mouth has been described as 'duck-billed', but in fact it was a shovel-shaped beak (not a bill), which they used to snap up tough plants that were then gnashed and ground with their teeth. Their teeth were continually being replaced



Paleontologists believe Parasaurolophus probably lived in herds for protection



Did you know?
Some palaeontologists have suggested Stegosaurus' plates were used for regulating body temperature

Stegosaurus

One of the best-known of all the dinosaurs, the Stegosaurus boasted a series of diamond-shaped bone plates and a tail that could kill

Maybe the most iconic genus of dinosaurs ever excavated, the Stegosaurus was a herbivorous titan, capable of consuming huge quantities of low-level foliage while protecting itself from predators with its vast armoured frame and potentially lethal spiked tail. The first example of Stegosaurus – from which its family name, Stegosauridae, derived – was unearthed in 1877 and since then four confirmed species of the dinosaur have been officially identified.

Each species demonstrates a similar structure and feature set, with each animal epitomising a large quadruped, sporting a series of diamond-shaped plates along its back. These large creatures were over eight metres (26 feet) long and were heavily built at over 3,000 kilograms (6,614 pounds). Interestingly, it's these plates that palaeontologists and academics know the least about, with a variety of arrangements, structures and uses suggested. When first unearthed it was speculated that they were used as a form of armoured defence against carnivorous predators. However, their positioning along the back and apparent bluntness has led to this theory being largely dismissed today. Instead, academics suggest that the plates were used as a decorative feature – perhaps in mating displays or to ward off Stegosaurus rivals in territory disputes.

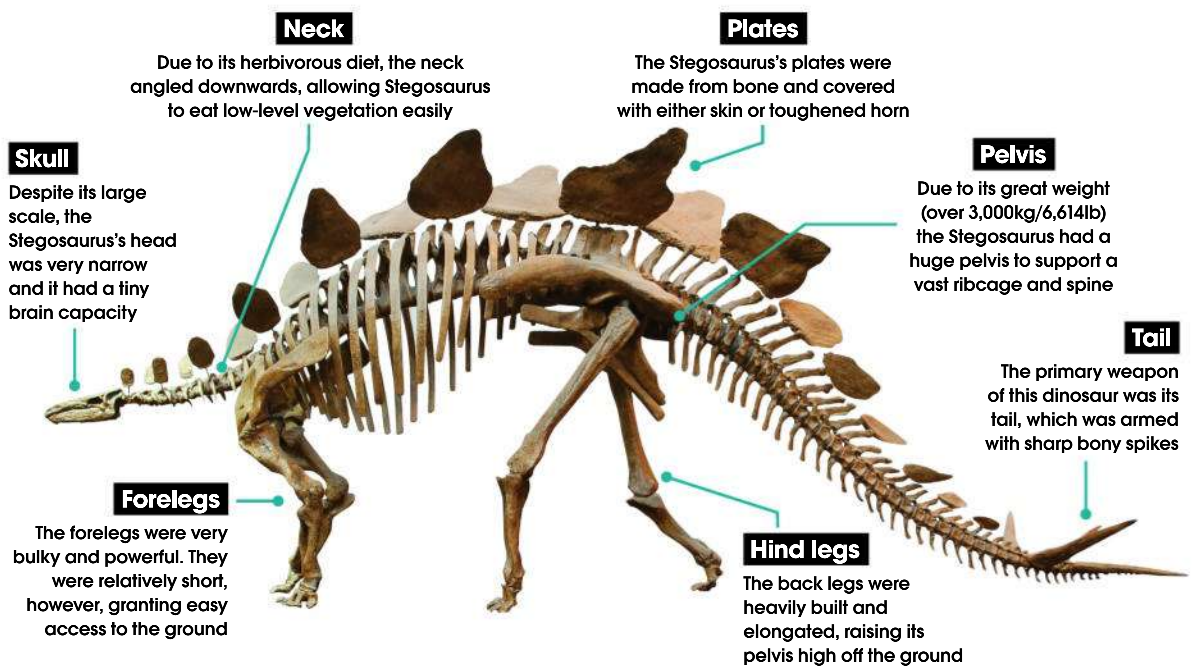
The field of palaeobiology reveals almost everything else about this genus. Studying fossilised evidence it is clear that due to Stegosaurus's very small and narrow skull, they had a tiny brain and so were not very intelligent – something seemingly confirmed by their primitive and mundane feeding habits. The low level of the animal's neck, short but bulky forelegs and raised pelvis/elongated hind legs indicate that Stegosaurus spent much of its daily routine consuming large quantities of low-lying foliage (such as ferns, cycads and conifers). This is confirmed by the shape and formation of its teeth and a low bite force.

Upon closer inspection of the dinosaur's legs it is also clear that it could not move very quickly. This is apparent as the discrepancy in size between the front and hind legs is so great that, if the creature ran at over eight kilometres (five miles) per hour, its longer back legs would cross over the forelegs leading it to fall.

Despite these shortcomings, Stegosaurus wasn't totally defenceless, as it boasted a flexible, armour-plated and spiked tail.

Taking Stegosaurus stenops as an example, the dinosaur had four dermal tail spikes of approximately 75 centimetres (29.5 inches) in length each, which extended out from the tail slightly off the horizontal plane. These spikes enabled the Stegosaurus to whip its tail and puncture the flesh of any attackers.

Stegosaurus anatomy



Ankylosaurus

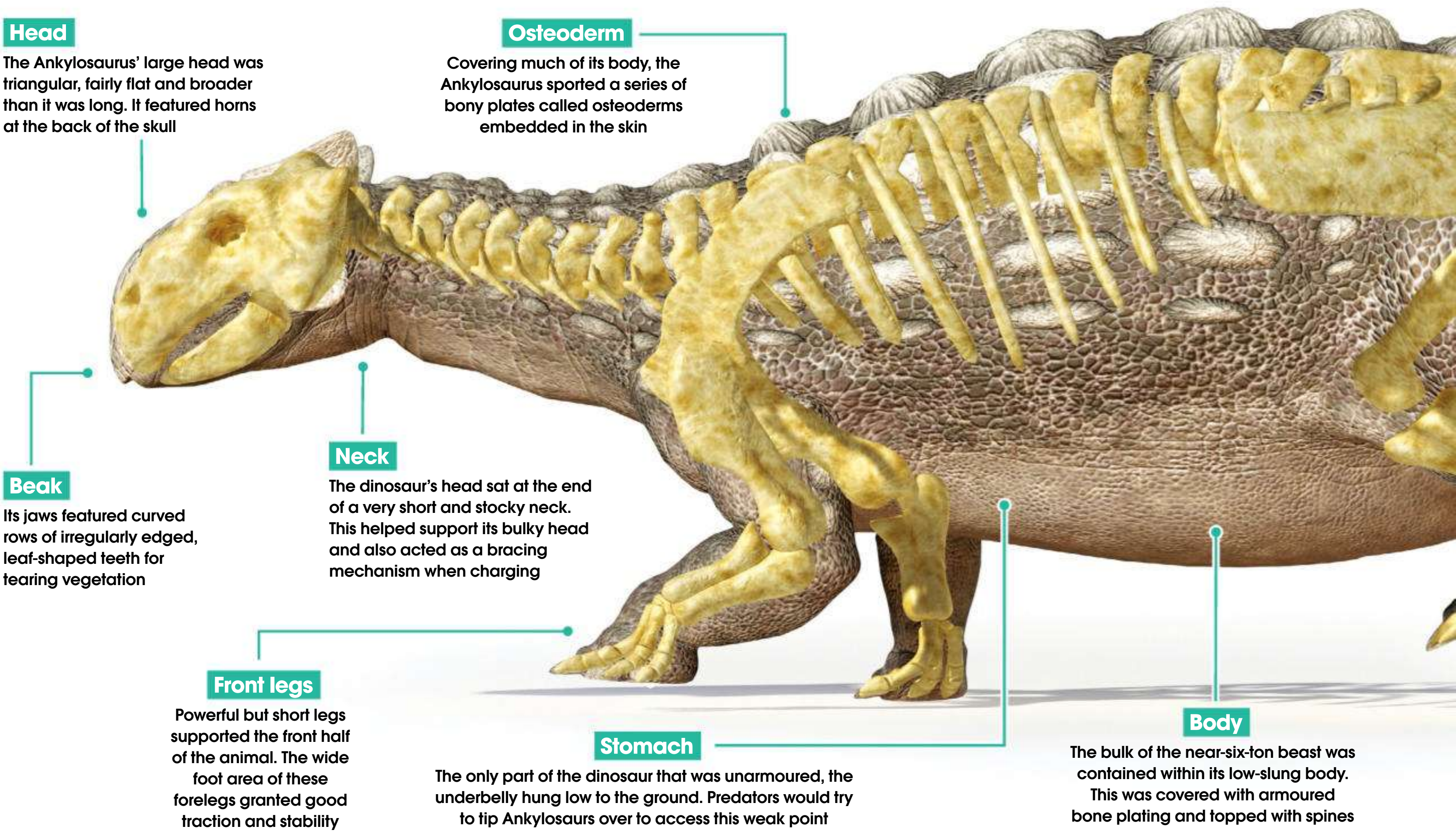
A club-wielding brute of a creature, this tough dino had the power to break bones

Ankylosaurus was one of the largest Ankylosaurs, a genus of armoured dinosaurs that lived throughout North America between 75 and 65 million years ago. Famous for both its brutal tail-mounted club and its immense bone plate armour, the Ankylosaurus was a defensive titan, capable of fending off rivals many times its size. Ankylosaurus' focus on defence was born out of its herbivorous nature, with its entire body geared towards the consumption of foliage. From its low-slung body, rows of leaf-shaped cropping teeth, short front legs, wide feet and cavernous stomach, the Ankylosaurus was the consummate browser, devouring vegetation whole with little shredding or chewing. Indeed, studies have indicated that the skull and jaw of the Ankylosaurus were structurally much tougher than many similar, contemporary dinosaurs.

In fact, evidence suggests that Ankylosaurus – and Ankylosaurs in general – were adept survivors. But despite their impressive armour, weaponry and sustainable diet, they could not cope with the Cretaceous-Tertiary extinction event that wiped out all terrestrial dinosaurs approximately 65 million years ago. Only a few fossils of this prehistoric herbivore have been excavated to date, with most coming from the Hell Creek Formation in Montana, US.

Club members only

The well-known tail club of the Ankylosaurus was one of the most lethal weapons sported by any dinosaur. The club was made from several large bone plates called osteoderms that were fused into the last few vertebrae of the animal's tail. Behind these vertebrae several others lined with thick, partially ossified tendons completed the club's handle, resulting in a structure that, when swung, was capable of dealing out a lot of damage. Indeed, a study in 2009 suggested that the tail clubs of fully grown Ankylosaurs could easily crush and break bone with a force capable of caving in an assailant's skull. Whether or not the animal purposely aimed the club to cause damage remains unclear at this point.

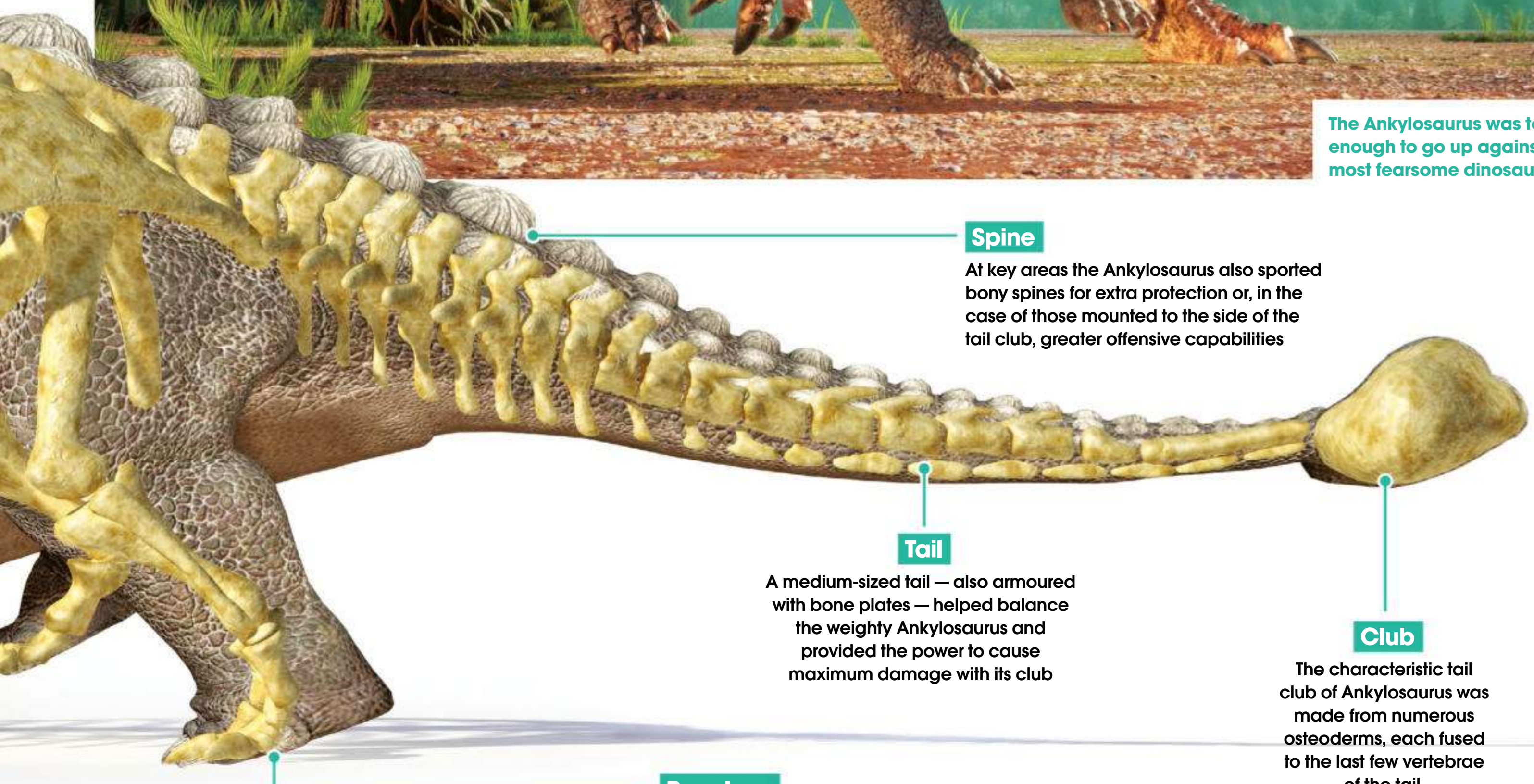


Tough stuff

The impressive armour of the Ankylosaurus was made up of a series of interlocking bone plates called osteoderms. These bone plates, which were locked into the skin, were bone overlaid with a tough layer of keratin. The plates were located over most of the body, but were not uniform in shape nor size, with some resembling flat diamonds — as seen on crocodiles and armadillos today — and others appearing like circular nodules.

The addition of these plates on top of the Ankylosaurus' head, along with a set of pyramidal horns to its rear and a row of triangular spikes mounted to each side of the tail club, meant that attacking this creature, even if you were an apex predator like the T rex, was not a good idea.

The Ankylosaurus was tough enough to go up against the most fearsome dinosaurs



Spine

At key areas the Ankylosaurus also sported bony spines for extra protection or, in the case of those mounted to the side of the tail club, greater offensive capabilities

Tail

A medium-sized tail — also armoured with bone plates — helped balance the weighty Ankylosaurus and provided the power to cause maximum damage with its club

Club

The characteristic tail club of Ankylosaurus was made from numerous osteoderms, each fused to the last few vertebrae of the tail.

Rear legs

Equally powerful – if not more so – but longer than the Ankylosaurus' forelegs, the rear legs reached up to about 1.7m at the hip

Compsognathus

This small but fierce dinosaur wasn't to be underestimated

One of the first discoveries of a near-complete fossil was a Compsognathus longipes specimen

When we think of dinosaurs, our mind will probably go to titans like Brachiosaurus, or gargantuan hunters like Tyrannosaurus rex. However, one of the most successful species of the Jurassic era was also one of the smallest dinosaurs ever discovered.

The Compsognathus was only about 70cm (2ft) long and 30cm (12in) tall. However, it made a very successful living out of hunting other small dinosaurs, reptiles, insects and other small animals around 145 to 140 million years ago. Being small may also have helped it to hide from larger predators of its time, such as the Allosaurus.

While Compsognathus was around the size of a large chicken, it's not thought to have had feathers like other theropods. No evidence of feathers has been found near Compsognathus fossils, and experts believe it probably had scales instead.


Compsognathus is not thought to have had feathers like many other theropods

Velociraptor

An adept predator and scavenger, but not quite the creature Hollywood would have us believe...

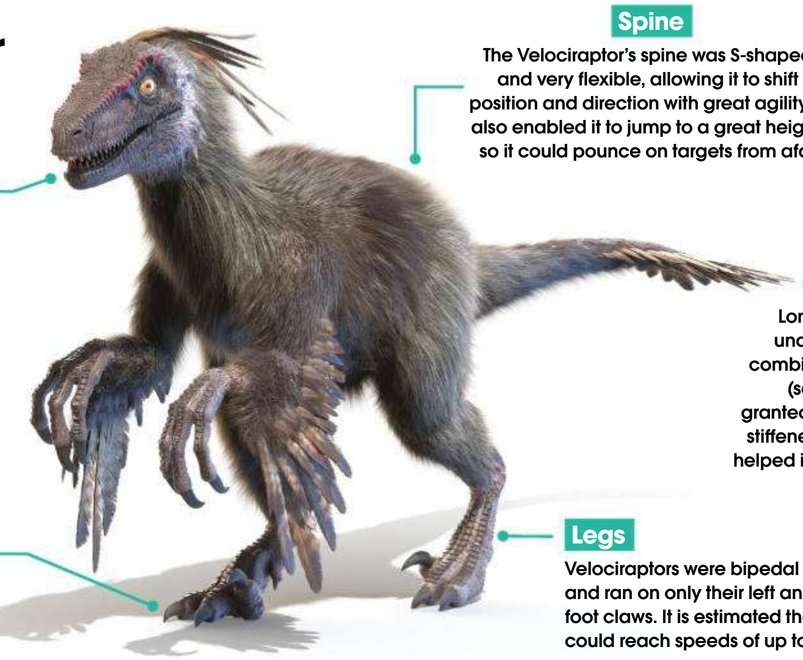
Velociraptors have been ingrained in public consciousness since the 1993 movie *Jurassic Park* showcased them as the most fearsome of apex predators. Smart, lethal and bloodthirsty, the Velociraptors of the film arguably stole the show. However, the movie was famed for its indulgence of artistic licence, with palaeontologists bemoaning the lack of historical accuracy. So what were these dinosaurs really like? Velociraptor, of which there are two verified species (V mongoliensis and V osmolskae) was a genus of dromaeosaurid ('running lizard') theropod dinosaur that lived in the Late Cretaceous period, about 75-71 million years ago. They were two metres long, just under a metre high, feathered and bipedal, running on two of their three toes per foot. They were native to modern-day central Asia (notably Mongolia), where they built large, ground-based nests to protect their young.

Velociraptors, though often living in close proximity to one another, were largely solitary and, while certain finds suggest they could have teamed up while chasing their quarry, they were not pack hunters, with evidence showing they would fight among themselves for feeding rights. In addition, their staple diet consisted of animals of equal size and weight to themselves or those smaller than them, with very little evidence suggesting they would attempt to bring down larger dinosaurs, such as the Tyrannosaurus rex à la *Jurassic Park*. Velociraptor hunting techniques revolved largely around their speed and agility. They could accelerate up to 64 kilometres per hour and jump long distances, as well as grip prey firmly with their unique, sickle-shaped claws (notably their enlarged 'killing claw'). These traits were partnered with a tendency to ambush prey rather than tackle their victims face on or from long range (see the 'Slash or subdue?' boxout for more).

Interestingly, however, while there's no doubt that Velociraptors hunted live prey, unearthed fossilised evidence suggests they were also incredibly active scavengers, with the species frequently feeding on carrion (pterosaur bones have been found in Velociraptor guts, for instance) and carcasses left over by other predators.

Velociraptors died out along with the remaining species of dromaeosauridae in the run up to, and as a result of, the Cretaceous-Tertiary mass-extinction event that occurred approximately 65.5 million years ago. Despite this, elements of their anatomy and appearance can still be seen today – albeit in heavily evolved forms – in many bird species.

Velociraptor anatomy



Teeth

The Velociraptor's jaw was lined with 28 widely spaced teeth on each side, with each one strongly serrated on the back edge far more than the front — a trait that helped it clamp on to prey once caught

Claws

A long, sickle-shaped claw was located on the second toe of each foot. These, as well as its other claws, were used to grip on to animals and gain purchase on the ground when running

Spine

The Velociraptor's spine was S-shaped and very flexible, allowing it to shift position and direction with great agility. It also enabled it to jump to a great height, so it could pounce on targets from afar

Tail

Long bony projections under the vertebrae, in combination with ossified (semi-bone) tendons, granted the Velociraptor a stiffened tail structure. This helped it to keep balanced and turn at speed

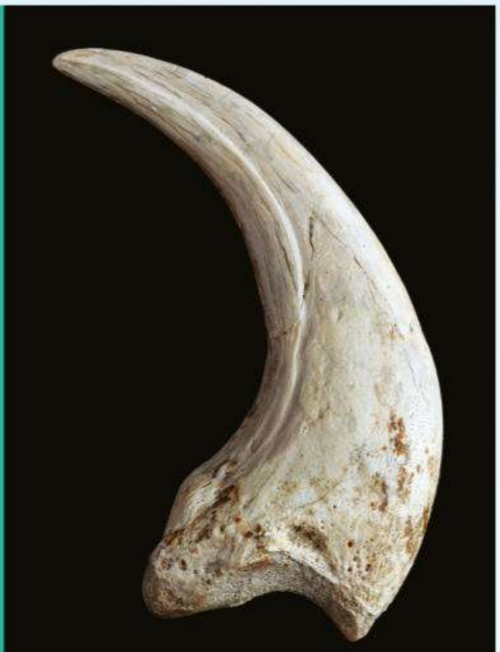
Legs

Velociraptors were bipedal dinosaurs and ran on only their left and right foot claws. It is estimated that they could reach speeds of up to 64kph

Slash or subdue?

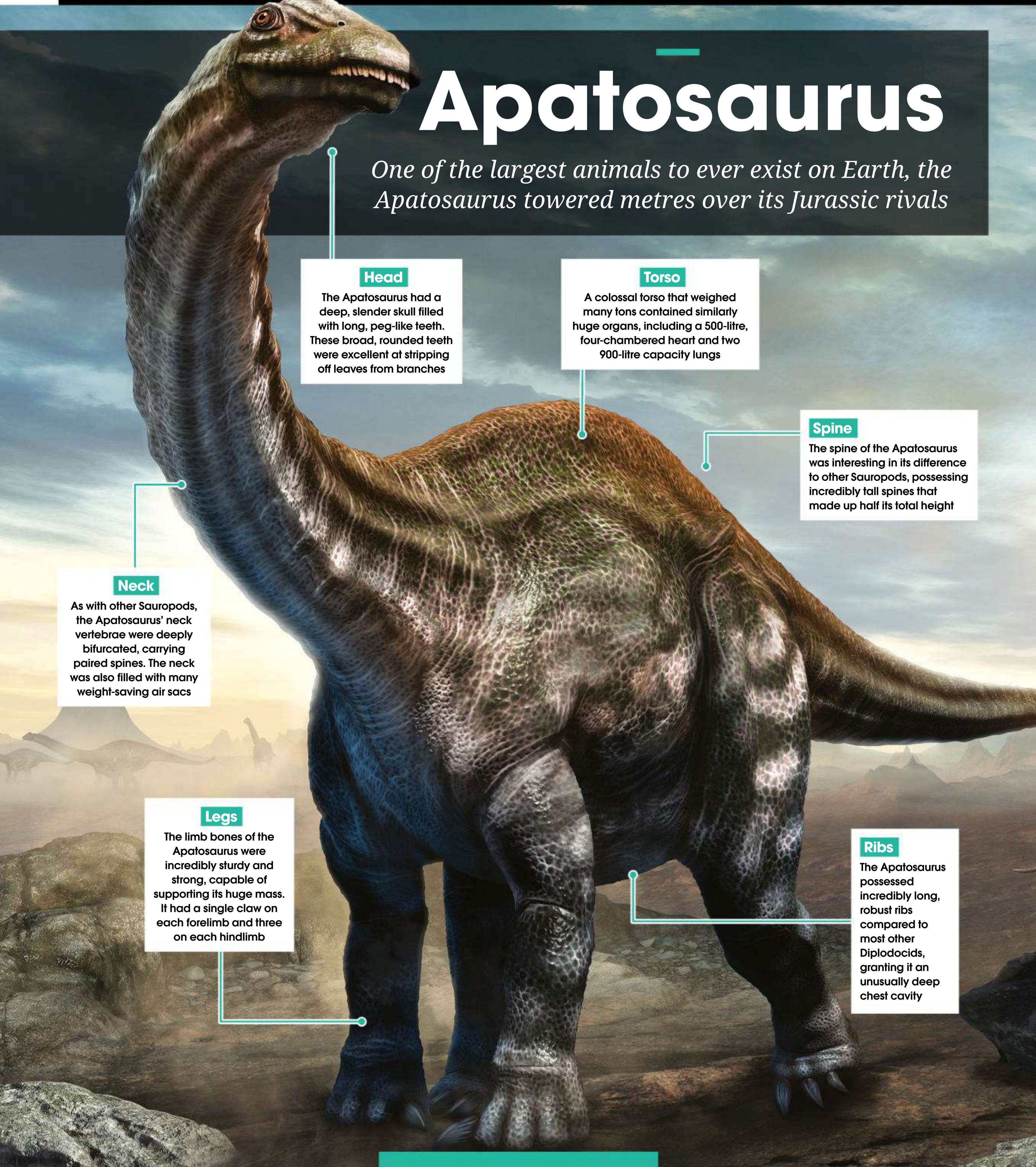
The majority of non-avian theropod dinosaurs are characterised by razor-sharp serrated teeth and talon-like recurved claws, the Velociraptor being no exception. Armed with a bounty of claws on both its hands and feet, the Velociraptor at first glance seems to be the perfect killing machine, capable of rapidly chasing down prey before shredding their flesh with one of their knife-like tools. Well, that was at least the commonly accepted theory among palaeontologists until 2011, before a study by a team of international dinosaur experts suggested an entirely different use for them. The study suggested that far from their claws – specifically the Velociraptor's much-touted 'killing claws' – being used to shred and slice prey in order to kill them prior to consumption, they were far more likely to be used in a similar way to the talons of modern-day hawks and eagles. This entails the birds using their talons as a gripping tool, snaring prey of a lesser body size, pinning them down with their own body weight and then often consuming them live with their beaks.

This theory is seemingly backed up by the Velociraptor's feet displaying morphology consistent with a grasping function, supporting a prey immobilisation model rather than the originally assumed combative one.



A fossilised claw from a Velociraptor. Evidence has emerged that has challenged the idea that this was used as a slashing weapon

Did you know?
Velociraptor hunting techniques revolved largely around their speed and agility



Apatosaurus

One of the largest animals to ever exist on Earth, the Apatosaurus towered metres over its Jurassic rivals

Head
The Apatosaurus had a deep, slender skull filled with long, peg-like teeth. These broad, rounded teeth were excellent at stripping off leaves from branches

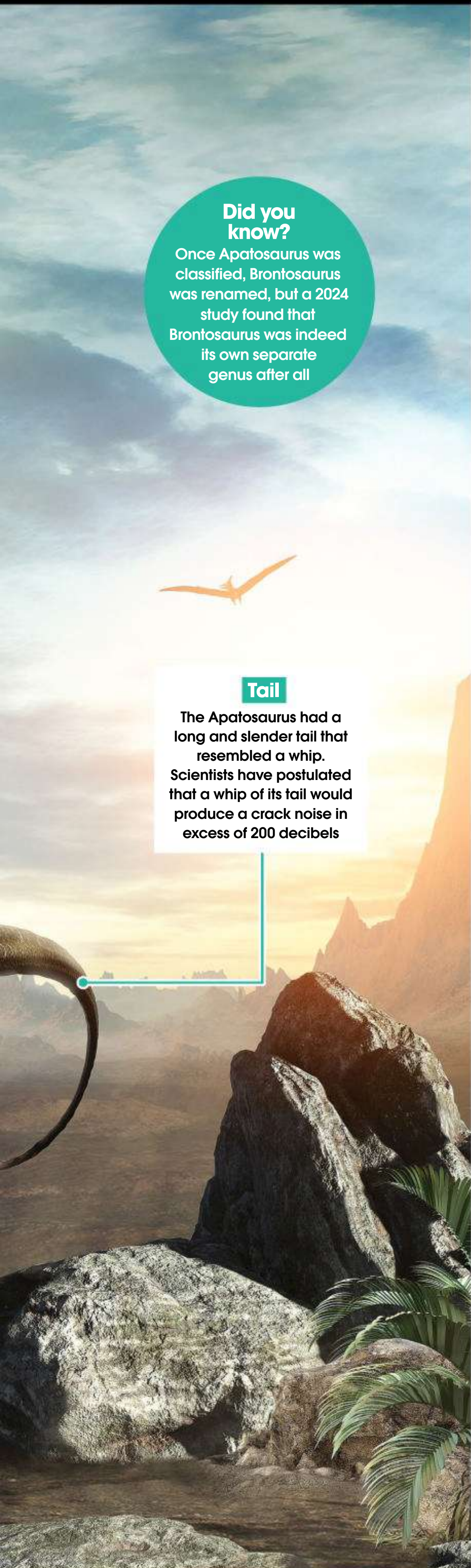
Torso
A colossal torso that weighed many tons contained similarly huge organs, including a 500-litre, four-chambered heart and two 900-litre capacity lungs

Spine
The spine of the Apatosaurus was interesting in its difference to other Sauropods, possessing incredibly tall spines that made up half its total height

Neck
As with other Sauropods, the Apatosaurus' neck vertebrae were deeply bifurcated, carrying paired spines. The neck was also filled with many weight-saving air sacs

Legs
The limb bones of the Apatosaurus were incredibly sturdy and strong, capable of supporting its huge mass. It had a single claw on each forelimb and three on each hindlimb

Ribs
The Apatosaurus possessed incredibly long, robust ribs compared to most other Diplodocids, granting it an unusually deep chest cavity



Did you know?

Once Apatosaurus was classified, Brontosaurus was renamed, but a 2024 study found that Brontosaurus was indeed its own separate genus after all

Tail

The Apatosaurus had a long and slender tail that resembled a whip. Scientists have postulated that a whip of its tail would produce a crack noise in excess of 200 decibels

Around four-times heavier than an African elephant, five-times longer than your car and almost six times the height of a full-grown human, the Apatosaurus was one of the largest dinosaurs of the Jurassic era and one of most gigantic creatures ever to walk the Earth.

As is typical with large dinosaurs of this period, the Apatosaurus (once mistakenly classified as the Brontosaurus) was a herbivore, consuming vast quantities of foliage and grasses over the lands that now form modern-day North America. Interestingly, despite its size, its name is derived from the Greek 'apate' and 'saurus', which translate as 'deception lizard', a name bestowed by its original discoverer, American palaeontologist Othniel Charles Marsh.

Prior to the 1970s, the Apatosaurus, along with many other Sauropods, were considered largely aquatic creatures that relied on being partially submerged in swamps and lakes to remain stable, a view seemingly confirmed by their colossal bulk. However, recent evidence has demonstrated that through a combination of massive limb bones and a series of weight-reducing internal air sacs located throughout the neck and spine, the Apatosaurus' home was, in fact, entirely land-based, with the titanic beast only spending time at water sources to drink.

Speaking of drinking, the Apatosaurus required gallons of water per day to remain healthy, while it also needed to process vast amounts of food, spending a large proportion of each day grazing. It did this with few predators, as only the largest carnivorous dinosaurs had any chance of bringing down an Apatosaurus, largely thanks to its size. It also had a deadly weapon in its tail, which was capable of being swung at great velocity at any foes.

Despite its defensive prowess, however, the Apatosaurus could not battle off extinction, with it falling to a medium-sized extinction event around 150 million years ago.

It is thought that the Apatosaurus evolved its long tail to counterbalance its equally long neck

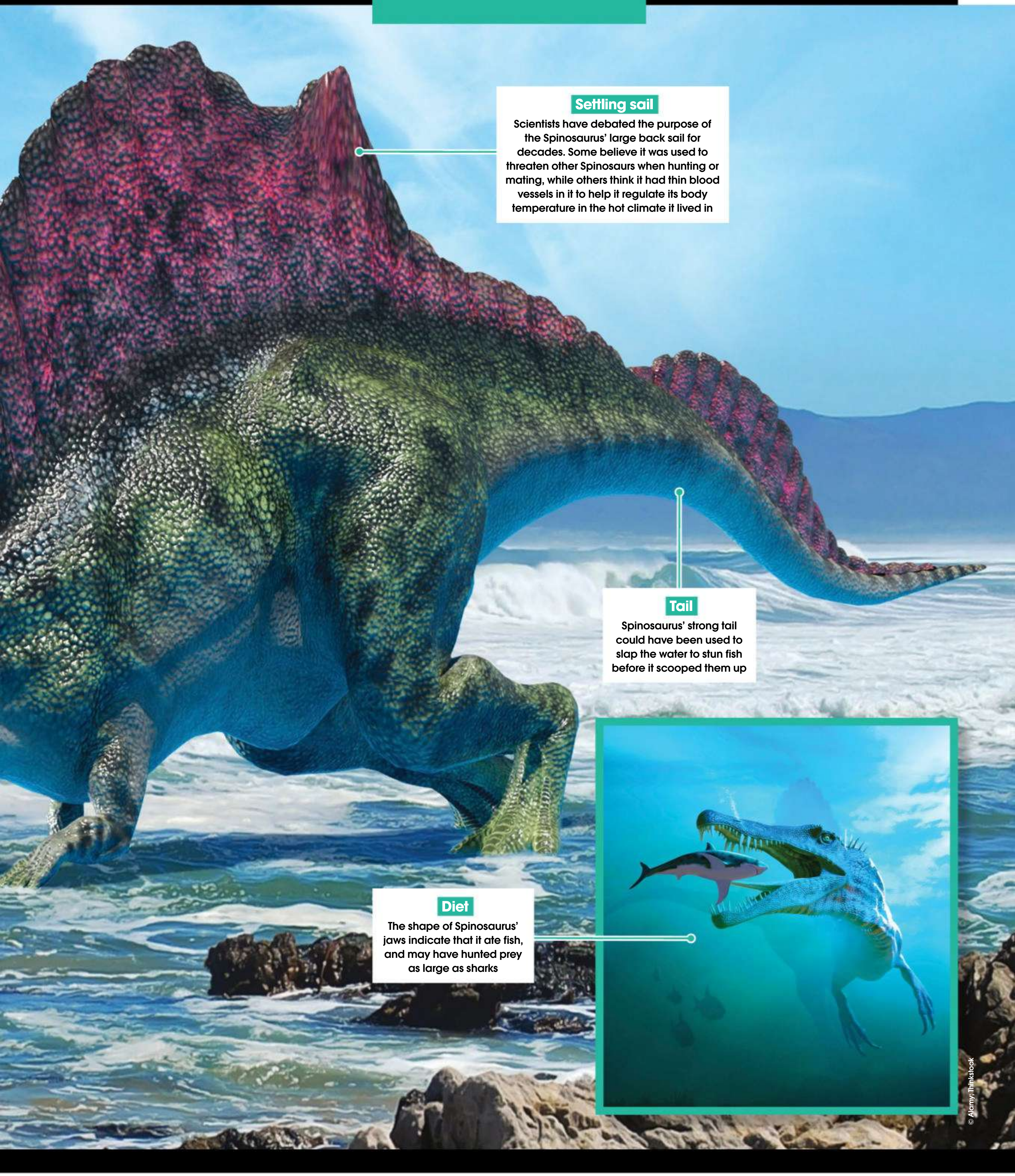
Spinosaurus

The discovery of this dinosaur made quite the splash

With the help of the astonishing sail on its back, Spinosaurus claims the title of the largest carnivorous dinosaur. Its discovery also changed what we thought we knew about predatory dinosaurs, which were previously thought to be solely terrestrial animals. Evidence suggests that Spinosaurus could have spent a lot of time in the water.

Scientists only have incomplete fossils to work from, so no one knows exactly how big Spinosaurus was, but many believe it could reach around 18 metres (60 feet) in length and weighed anything from 7-20 tons. It was larger than even the Giganotosaurus, but thinner than both the Giga and the Tyrannosaurus rex. However, it did something neither the Giga nor the T rex did: hunt in water.

With its long snout, the Spinosaurus terrorised waterways, lurking like a crocodile, its spine sticking out of the water like a shark fin, possibly to ward off other Spinosaurs from its territory, ready to strike at anything venturing too close.



Settling sail

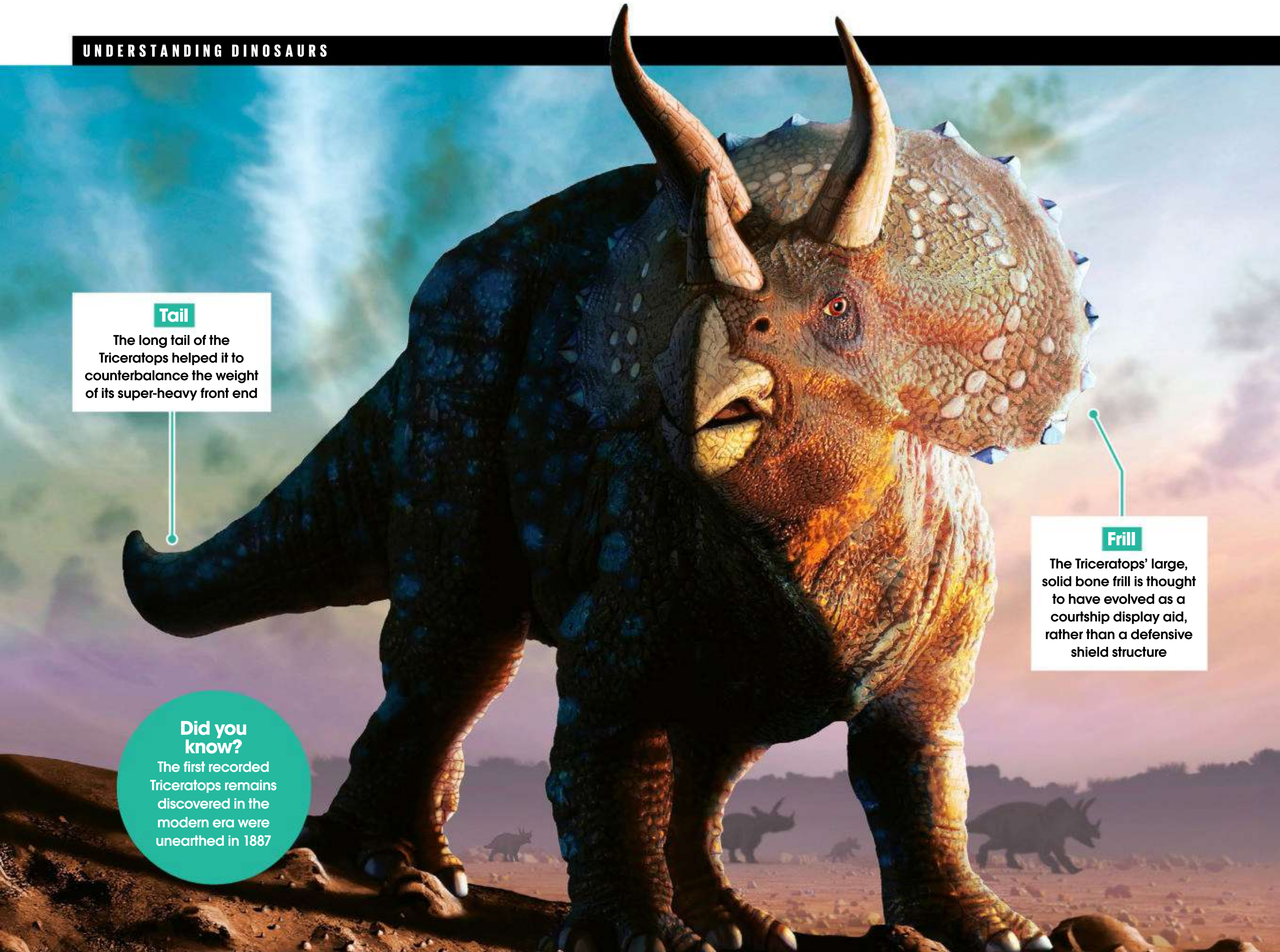
Scientists have debated the purpose of the Spinosaurus' large back sail for decades. Some believe it was used to threaten other Spinosaurs when hunting or mating, while others think it had thin blood vessels in it to help it regulate its body temperature in the hot climate it lived in

Tail

Spinosaurus' strong tail could have been used to slap the water to stun fish before it scooped them up

Diet

The shape of Spinosaurus' jaws indicate that it ate fish, and may have hunted prey as large as sharks



Tail
The long tail of the Triceratops helped it to counterbalance the weight of its super-heavy front end

Frill
The Triceratops' large, solid bone frill is thought to have evolved as a courtship display aid, rather than a defensive shield structure

Did you know?
The first recorded Triceratops remains discovered in the modern era were unearthed in 1887

Triceratops

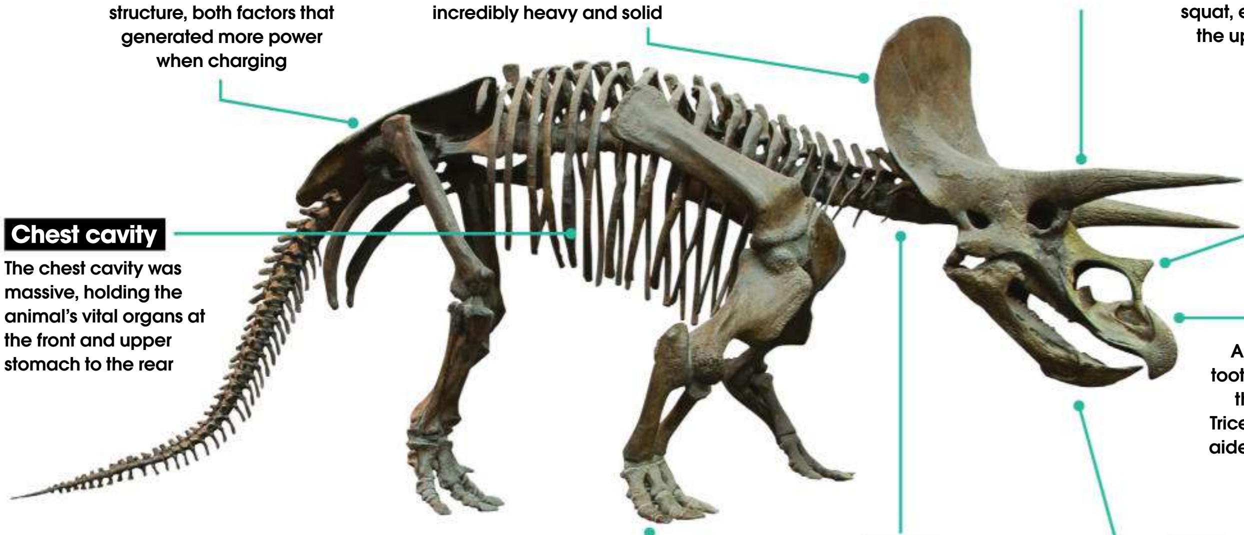
One of the most well-known dinosaurs, the Triceratops was a herbivorous titan that was very well equipped for a fight

Triceratops is a genus of herbivorous dinosaur that comprises two validated species – Triceratops horridus and Triceratops prorsus, both of which roamed Earth during the Late Cretaceous period (68-65 MYA) before being eradicated in the K-T mass-extinction event that wiped out all dinosaurs.

Triceratops were large, rhinoceros-like animals that weighed many tonnes – a fully grown adult would be expected to weigh in the region of seven tonnes. They were heavily armoured with reinforced bone horns, which could exceed 70 centimetres (28 inches) and a solid bone frill, and hugely powerful thanks to their sturdy frame. These traits, combined, made both species of Triceratops a fearsome foe to potential predators, capable of puncturing flesh and shattering bone with their sharp horns when charging.

In terms of anatomy, the Triceratops genus is incredibly interesting, not least because many of its parts' functions are still debated today in the field of palaeontology. A good example of this can be seen by analysing a typical Triceratops skull, which – aside from typically measuring a

Triceratops anatomy



whopping two metres (6.6 feet) in length – sported three horns as well as a fluted, extravagant rear frill. The horns, from which the genus gets its name, and frill have been successfully argued by palaeontologists to have been used for self-defence against predators, with close examination of unearthed specimens revealing battle scars, cuts, punctures and cracks. However, modern scholars also postulate that both skull features, along with the elongated nature of the skull itself, most likely also evolved as courtship aids, with potential mates selected on the size and shape of these features. It has also been suggested that the frill may have helped Triceratops regulate their body temperature in a similar manner to the plate-laden Stegosaurus.

Other anatomical areas of interest lie in this dinosaur's large bird-like beak and hips. Indeed, it is because of these particular features that this genus has been used as a reference point in the definition of all dinosaurs – ie all dinosaurs are descendants of the most recent common ancestor of Triceratops and, as such, this common ancestor is also that of birds prevalent throughout the world today. It's important to note here that modern birds did not descend from Triceratops directly, but rather from its common ancestor with all other dinosaurs; today's birds in fact originate from saurischian dinosaurs.

The fundamental diet of the Triceratops was largely dictated by – and most likely co-evolved with – its low-slung posture and head position, which was located close to the ground. As a consequence of these factors, as well as its deep and narrow beak and sharp teeth batteries, both species of Triceratops most likely consumed large amounts of low-growth ferns, palms and cycads, plucking the plants with their beaks and then shredding the fibrous material with their teeth.

The Triceratops' main potential predators were carnivorous theropod dinosaurs such as the Tyrannosaurus rex. However, while modern-day depictions of these two prehistoric titans are often far-fetched, Triceratops specimens have been discovered with T rex bite marks, and even one where the herbivore had one of its brow horns snapped off entirely.

Carnotaurus

Meet one of the weirdest dinosaurs to have walked the Earth

The Carnotaurus was one of the Late Cretaceous period's most feared predators. It once stalked across the land with its bright, beady eyes, box-shaped head and distinctive bull-like horns. Standing around four metres tall and nine metres long, these unusual-looking giant theropods were the distant South American cousins of the T rex.

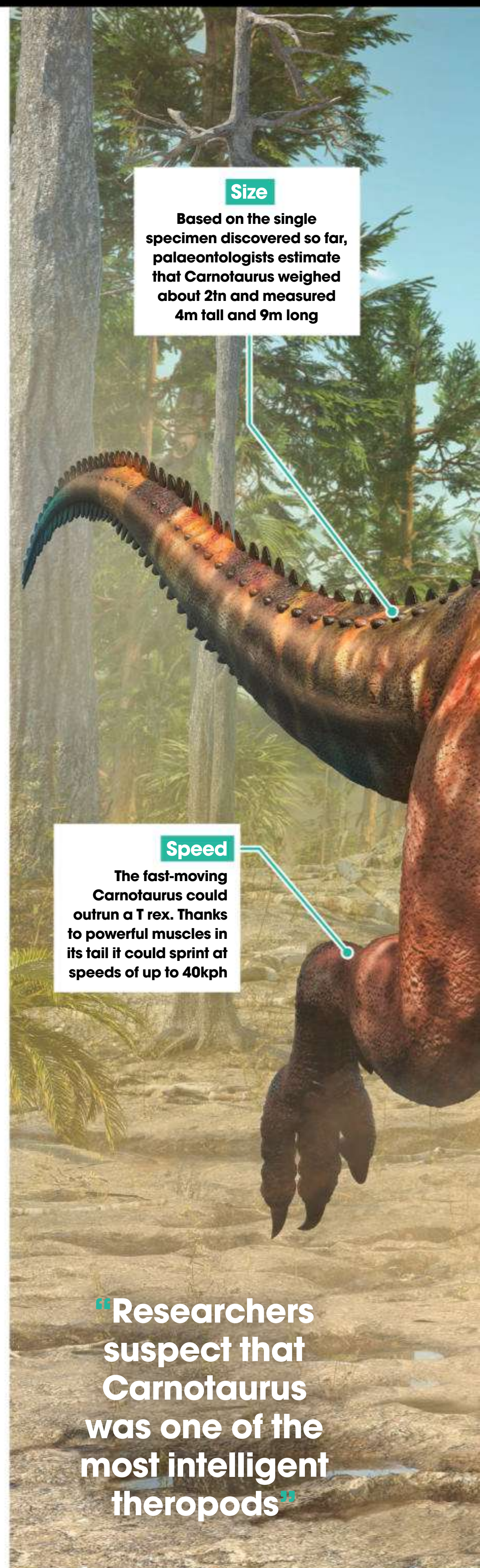
The Carnotaurus' most distinctive feature, however, is its comical – and probably useless – tiny arms. While these wouldn't have made it any less ferocious if you were confronted with one, they do pose an evolutionary puzzle for palaeontologists today (see the boxout on the right).

Only one Carnotaurus fossil has ever been discovered, unearthed in Argentina by palaeontologist Jose Bonaparte in 1985. However, it is almost a full skeleton and impressively detailed – including fossilised impressions of its skin in the surrounding Earth – making it a very rare find indeed. The remains have given palaeontologists a remarkable insight into the Carnotaurus' anatomy, posture, habitat and diet.

It's not hard to see why palaeontologists chose the name Carnotaurus, meaning 'meat-eating bull'. Its distinctive horns are thought to have been used by males to fight one another, literally butting heads when competing for territory or to impress females.

Like many other large theropods, Carnotaurus were carnivores and so had the sharp teeth to match. If their terrifying backwards-curving, flesh-tearing teeth were not enough to scare you, researchers suspect that the crafty Carnotaurus was also one of the most intelligent theropods – it could definitely outrun you, and it may have even been able to outsmart you.

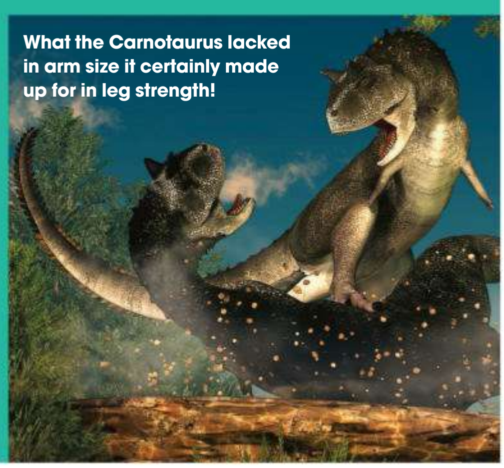
Did you know?
In the movie *Jurassic World*, Carnotaurus DNA was used to genetically engineer the Indominus rex hybrid

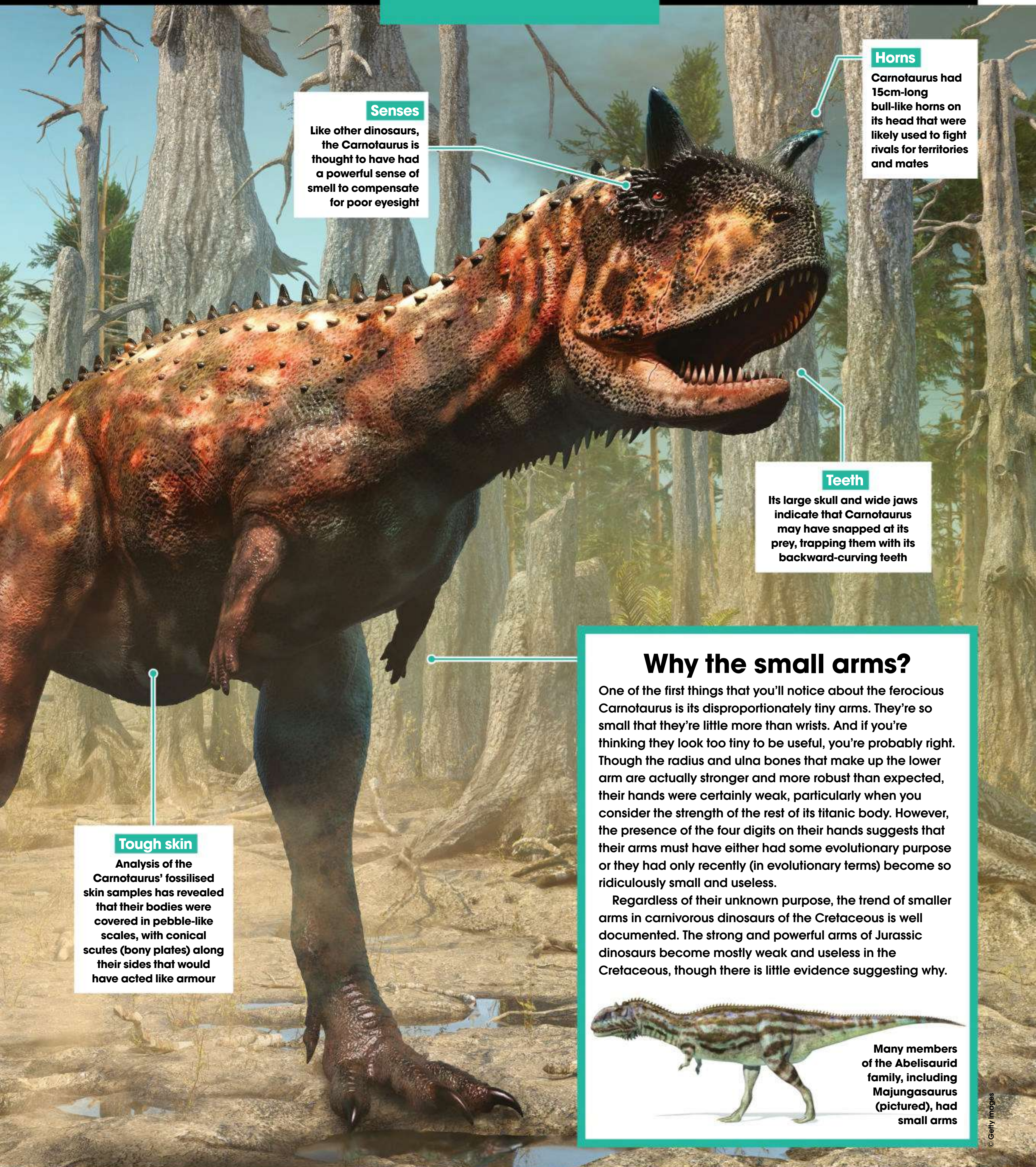


"Researchers suspect that Carnotaurus was one of the most intelligent theropods"

Roarsome sprinter

Carnotaurus was a champion sprinter, capable of reaching speeds of 40kph. Two of the most striking pieces of evidence for this come from analysing the leg and tail of the fossil specimen. Its thigh bones were adapted to withstand bending movements when running, while bulky muscles in its tail also provided power. The caudofemoralis (a pair of muscles that ran either side of the tail) attached to a prominent ridge on the thigh bone to pull the leg backwards when contracted. The muscles were anchored to the tail bones, which, in the case of the Carnotaurus, were not T-shaped like slower-moving animals but instead formed a V-shape. This adaptation created more space for bigger caudofemoralis muscles, which made up some 15 per cent of the Carnotaurus' entire body mass – larger than any other theropod. Because of this super sprinting ability, it's thought that Carnotaurus would have been ambush predators, employing bursts of speed to catch their prey.


What the Carnotaurus lacked in arm size it certainly made up for in leg strength!



Why the small arms?

One of the first things that you'll notice about the ferocious Carnotaurus is its disproportionately tiny arms. They're so small that they're little more than wrists. And if you're thinking they look too tiny to be useful, you're probably right. Though the radius and ulna bones that make up the lower arm are actually stronger and more robust than expected, their hands were certainly weak, particularly when you consider the strength of the rest of its titanic body. However, the presence of the four digits on their hands suggests that their arms must have either had some evolutionary purpose or they had only recently (in evolutionary terms) become so ridiculously small and useless.

Regardless of their unknown purpose, the trend of smaller arms in carnivorous dinosaurs of the Cretaceous is well documented. The strong and powerful arms of Jurassic dinosaurs become mostly weak and useless in the Cretaceous, though there is little evidence suggesting why.

Many members of the Abelisaurid family, including Majungasaurus (pictured), had small arms

Sauropod fossils have been found that show evidence of Allosaurus attacks

Allosaurus may have hunted in packs, making them even more formidable predators

Tail
Allosaurus' long, muscular tail helped balance the weight of its body

Allosaurus

Meet the fiercest predator of its time

If you were a huge or heavily armoured herbivore living in the Late Jurassic era, not many things would worry you. The exception? A 12-metre (40-foot) long hunter with huge, sharp claws and teeth like giant daggers ambushing you and chasing you down. That's what daily life was like for the creatures who lived alongside the Allosaurus around 145 million years ago.

Allosaurus was one of the first well-known theropod dinosaurs to be discovered and studied, with initial fossils being discovered in the 1870s. The name Allosaurus means 'strange lizard', as its backbone fragments were distinctly different to other dinosaur spines that had been found before.

It was the biggest, most dangerous predator in Earth's history at the time, the Allosaurus and its 20-centimetre (eight-inch) claws would regularly take on – and take down – prey as well protected as the armour-plated Stegosaurus or as big as the massive Apatosaurus. It also had jagged teeth that curved backwards into its mouth (similar to snakes today), so when it bit into its prey, any attempt to escape would only make the victim more stuck in the giant hunter's death grip.

Roaming the Earth for around 10 million years, the Allosaurus was even more successful as the king of hunters than the more famous T rex.

Paleontologists have found a Stegosaurus fossil with an Allosaurus bite mark on the neck plate

Iguanodon

One of the very first dinosaurs to be discovered by humankind

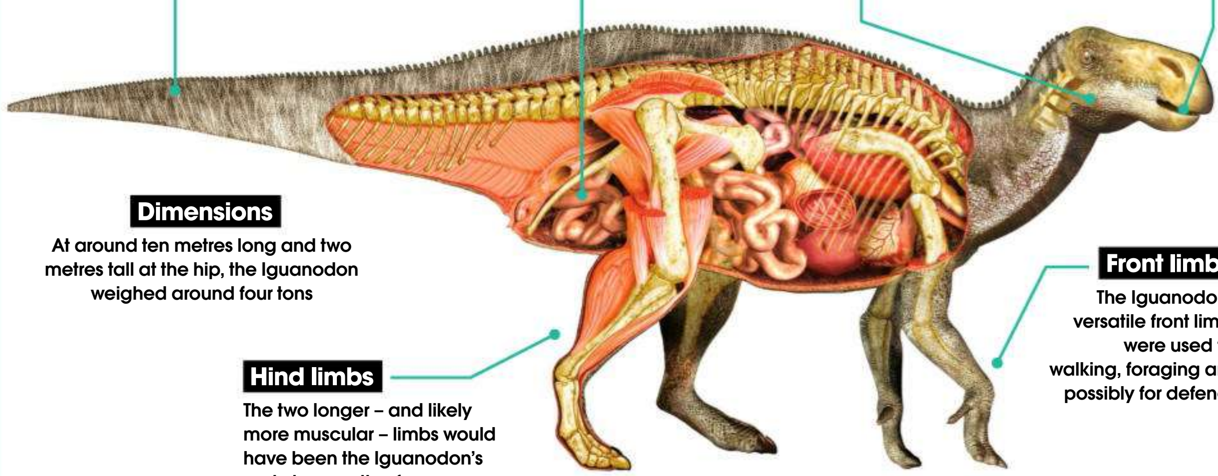
It's very easy to find ourselves captivated by big, fearsome carnivores. We imagine them prowling the plains and forests of the Mesozoic Era, stalking and hunting the peaceful herbivores and roaring with vindication as they overcome their prey and claim a meal. But we often neglect to pay attention to their prey, to the herbivores that have merited an equal place in natural history. Some – such as the Iguanodons – also have a key place in our own history, marking a milestone in our fledgling efforts to study dinosaurs.

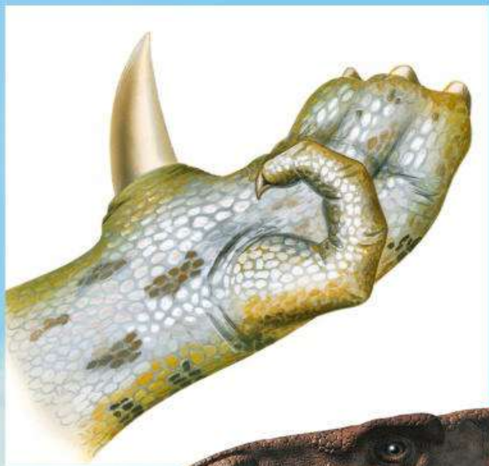
When its fossils were uncovered in England in the early 19th century, the Iguanodon was only the second ever genus to be classified as a dinosaur. After recognising that the newly discovered specimen had teeth similar to an iguana's, the Iguanodon earned its name and planted the seeds for the later realisation that dinosaurs had been, in fact, reptiles. Our perception of the Iguanodon has vastly changed and developed through the years, and today we can enjoy a fairly clear picture of how this hulking herbivore would have lived over 100 million years ago.

Iguanodon species existed in the Late Jurassic and Early Cretaceous periods. They had evolved to become effective grazing animals: with a flexible jaw for chewing; flat, rigid teeth for grinding fibrous plants; and the ability to stand back on two legs and use their ten-metre-long bodies to reach the highest leaves.

It's thought that Iguanodons would roam in herds for protection, similar to the herbivorous mammals of today, especially as they lacked the formidable horns and armour of other dinosaurs. However, they may have benefitted from the presence of other such herbivores, as multiple species journeyed together for mutual protection. Their world, like ours today, was a competitive one. But despite this the Iguanodon was able to prosper in many regions, including modern-day North Africa, Europe, Asia, Australia and North America.

Iguanodon anatomy



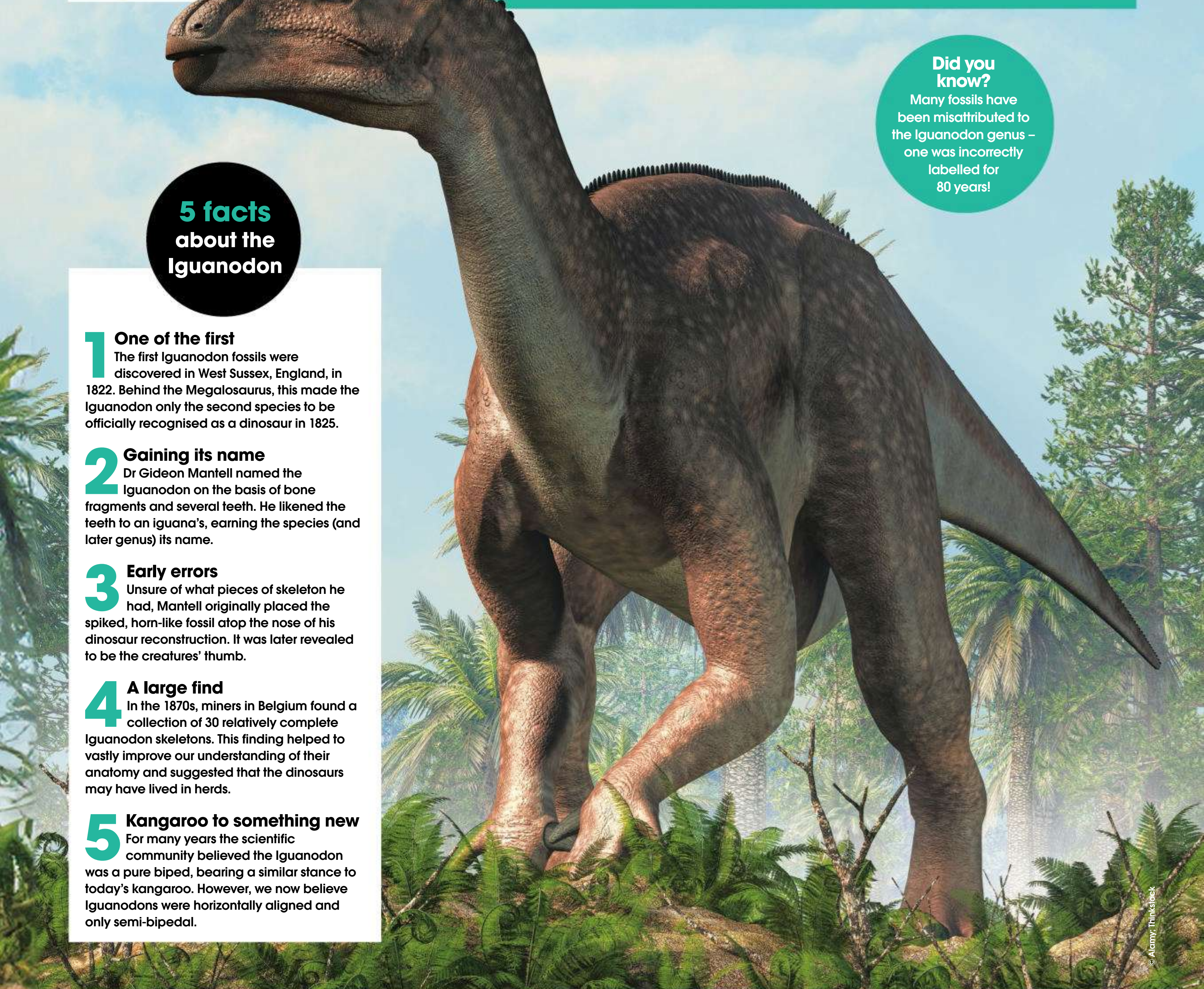


Thumbs-up for Iguanodons

The Iguanodon's hand anatomy has captivated palaeontologists since its discovery. The species possessed a five-digit hand composed of three thick, blunt fingers, one unbound fourth finger that protruded laterally from its palm, and an intriguing thumb-spike. We understand that the spike originated via fused thumb joints, but its function remains a mystery.

Some have postulated that the spike's primary use was for defence, either from potential predators or from rival Iguanodons. They argue that the dinosaur would have used the sharp thumbs to stab at opponents when engaged in close combat. Some go further and suggest that the spike may have even housed a venom gland, adding an extra layer of lethality to the hand-wielded weapon.

Others believe the curious feature had a more peaceful purpose. It may have simply been used for breaking into nuts and seeds, or potentially for stripping foliage from trees before consumption.



Did you know?
Many fossils have been misattributed to the Iguanodon genus – one was incorrectly labelled for 80 years!

5 facts about the Iguanodon

1 One of the first
The first Iguanodon fossils were discovered in West Sussex, England, in 1822. Behind the Megalosaurus, this made the Iguanodon only the second species to be officially recognised as a dinosaur in 1825.

2 Gaining its name
Dr Gideon Mantell named the Iguanodon on the basis of bone fragments and several teeth. He likened the teeth to an iguana's, earning the species (and later genus) its name.

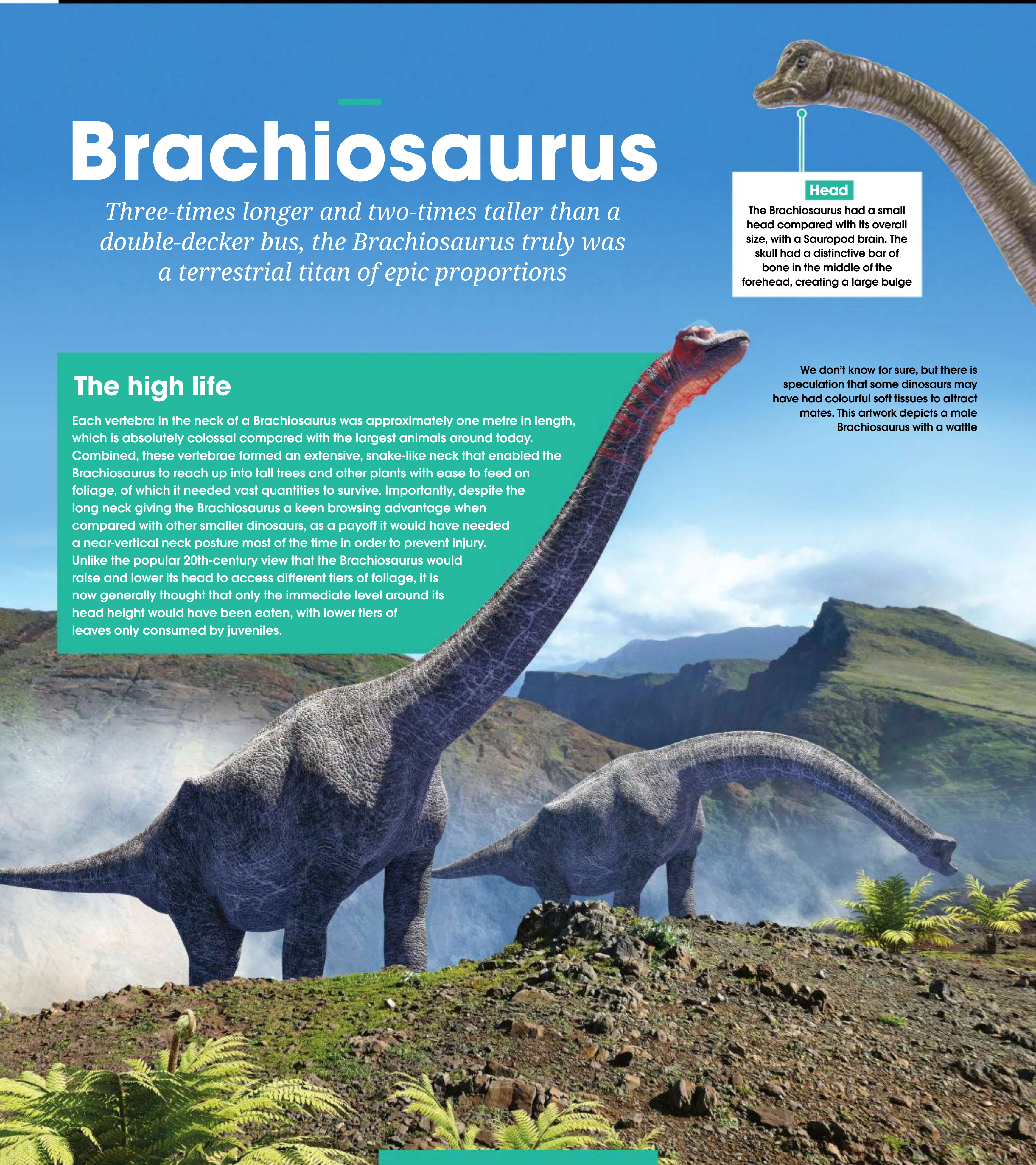
3 Early errors
Unsure of what pieces of skeleton he had, Mantell originally placed the spiked, horn-like fossil atop the nose of his dinosaur reconstruction. It was later revealed to be the creatures' thumb.

4 A large find
In the 1870s, miners in Belgium found a collection of 30 relatively complete Iguanodon skeletons. This finding helped to vastly improve our understanding of their anatomy and suggested that the dinosaurs may have lived in herds.

5 Kangaroo to something new
For many years the scientific community believed the Iguanodon was a pure biped, bearing a similar stance to today's kangaroo. However, we now believe Iguanodons were horizontally aligned and only semi-bipedal.

Brachiosaurus

Three-times longer and two-times taller than a double-decker bus, the Brachiosaurus truly was a terrestrial titan of epic proportions



Head

The Brachiosaurus had a small head compared with its overall size, with a Sauropod brain. The skull had a distinctive bar of bone in the middle of the forehead, creating a large bulge

We don't know for sure, but there is speculation that some dinosaurs may have had colourful soft tissues to attract mates. This artwork depicts a male Brachiosaurus with a wattle

The high life

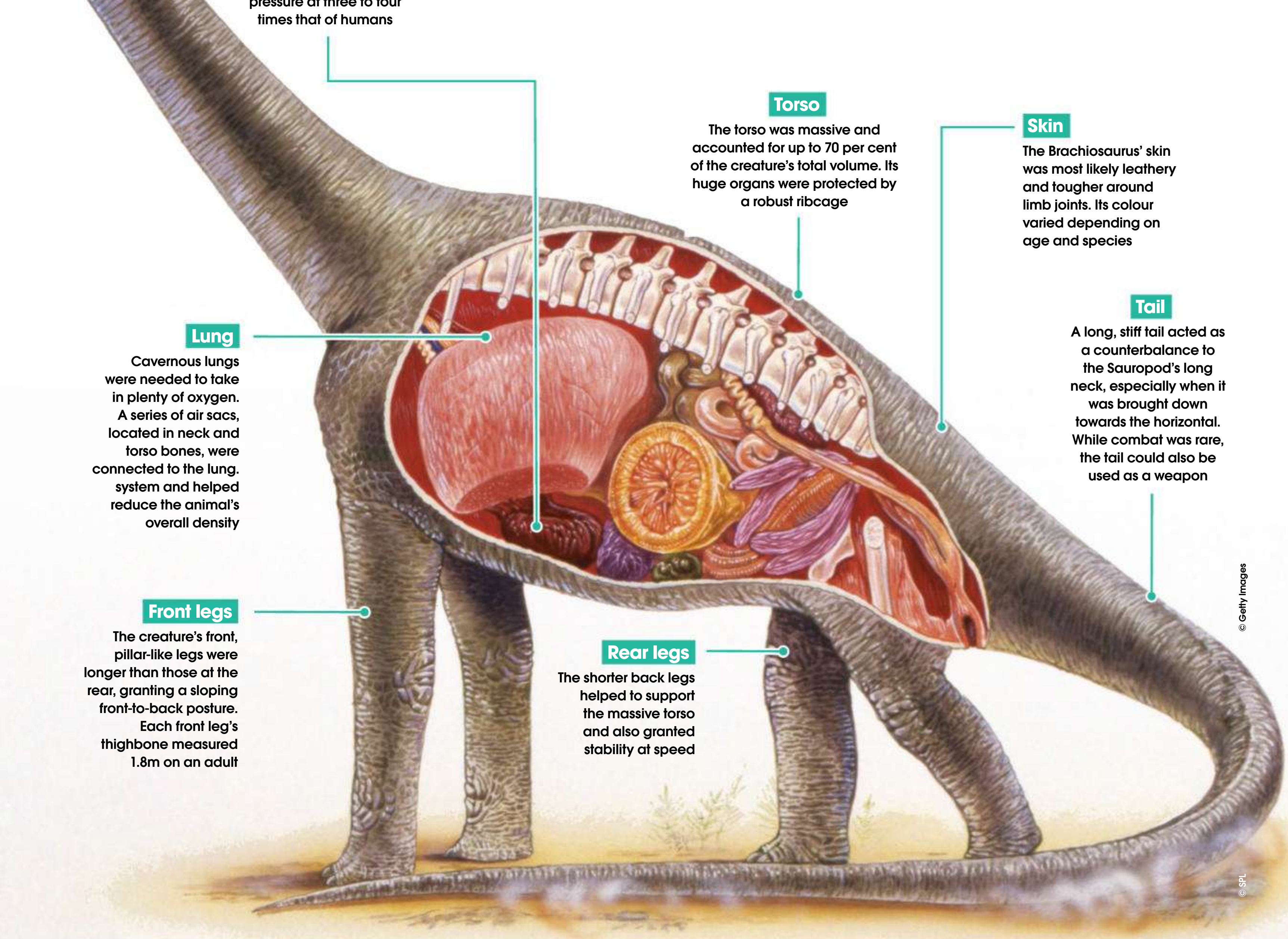
Each vertebra in the neck of a Brachiosaurus was approximately one metre in length, which is absolutely colossal compared with the largest animals around today. Combined, these vertebrae formed an extensive, snake-like neck that enabled the Brachiosaurus to reach up into tall trees and other plants with ease to feed on foliage, of which it needed vast quantities to survive. Importantly, despite the long neck giving the Brachiosaurus a keen browsing advantage when compared with other smaller dinosaurs, as a payoff it would have needed a near-vertical neck posture most of the time in order to prevent injury. Unlike the popular 20th-century view that the Brachiosaurus would raise and lower its head to access different tiers of foliage, it is now generally thought that only the immediate level around its head height would have been eaten, with lower tiers of leaves only consumed by juveniles.

Brachiosaurus was a genus of Sauropod dinosaur that roamed the Earth during the Late Jurassic period (circa 155-140 million years ago). They are characterised, like many Sauropods of the time, by their huge necks and comparatively tiny skulls and brains. Currently only one species has been officially confirmed — the B altithorax — though others have been suggested.

Interestingly, like other Sauropods, these creatures, despite weighing an estimated 60 tons and measuring up to 30 metres long, were actually colossal vegetarians, with their diet comprising solely of foliage.

Their evolution of such a long neck (see 'The high life' boxout for more details) seems to be intrinsically linked to their diet, with the elevated head position enabling them to access leaves unavailable to shorter species. This dominion over a food source is also a major factor behind their generally massive proportions, with millions of years of domination allowing them to grow to sizes far in excess of rival creatures from the same era. The epic size of the Brachiosaurus was also its primary form of defence when it came to predators. Once fully grown, their legs would have resembled tree trunks and these, partnered with a heavy, stocky tail, made them an extremely difficult dinosaur to tackle.

While their size and domination granted many benefits, it was also a contributor to the Brachiosaurus' demise, with resource depletion and climate change leading to their background extinction around 145 million years ago.



Archaeopteryx

Is it a bird? Yes. Is it a dinosaur? Yes

Dental clues

Archaeopteryx's teeth are one of several features that proves it was a link between dinosaurs and birds

Diet

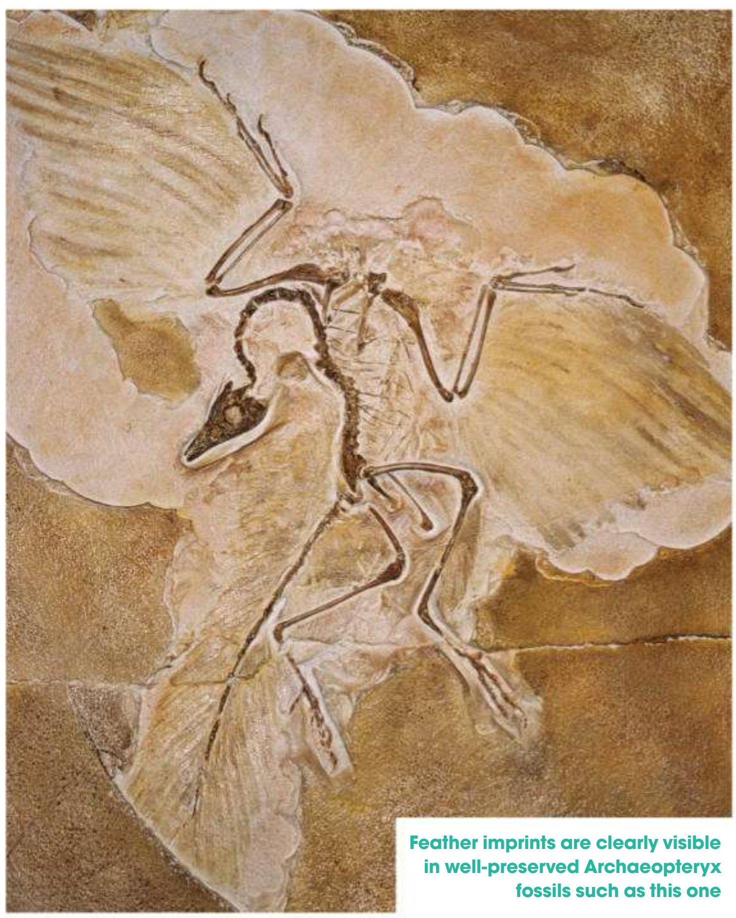
Archaeopteryx were mostly carnivorous, so would eat small animals like insects

"Archaeopteryx escaped would-be predators by doing something no other dinosaur had done before: it took to the skies"

Archaeopteryx wasn't very big, only about half a metre long and standing no taller than your shin. But when it appeared in the Late Jurassic, about 147 million years ago, it changed Earth's history. The reason? It's one of the first ever birds.

Unlike flying Pterosaurs (which were not technically dinosaurs), the last of which all went extinct 66 million years ago and bear no relation to today's birds, Archaeopteryx is a direct ancestor of the feathered fowls you might be looking at out of your window right now. But it was also a dinosaur, as its conical dinosaur teeth and theropod legs prove. It fed on small reptiles, mammals and insects and escaped would-be predators by doing something no other dinosaur had done before: it took to the skies.

Because its wings were asymmetrical, scientists still aren't sure whether Archaeopteryx could take flight from the ground, like many birds today, or whether it had to launch from trees or cliffs to glide on the air.

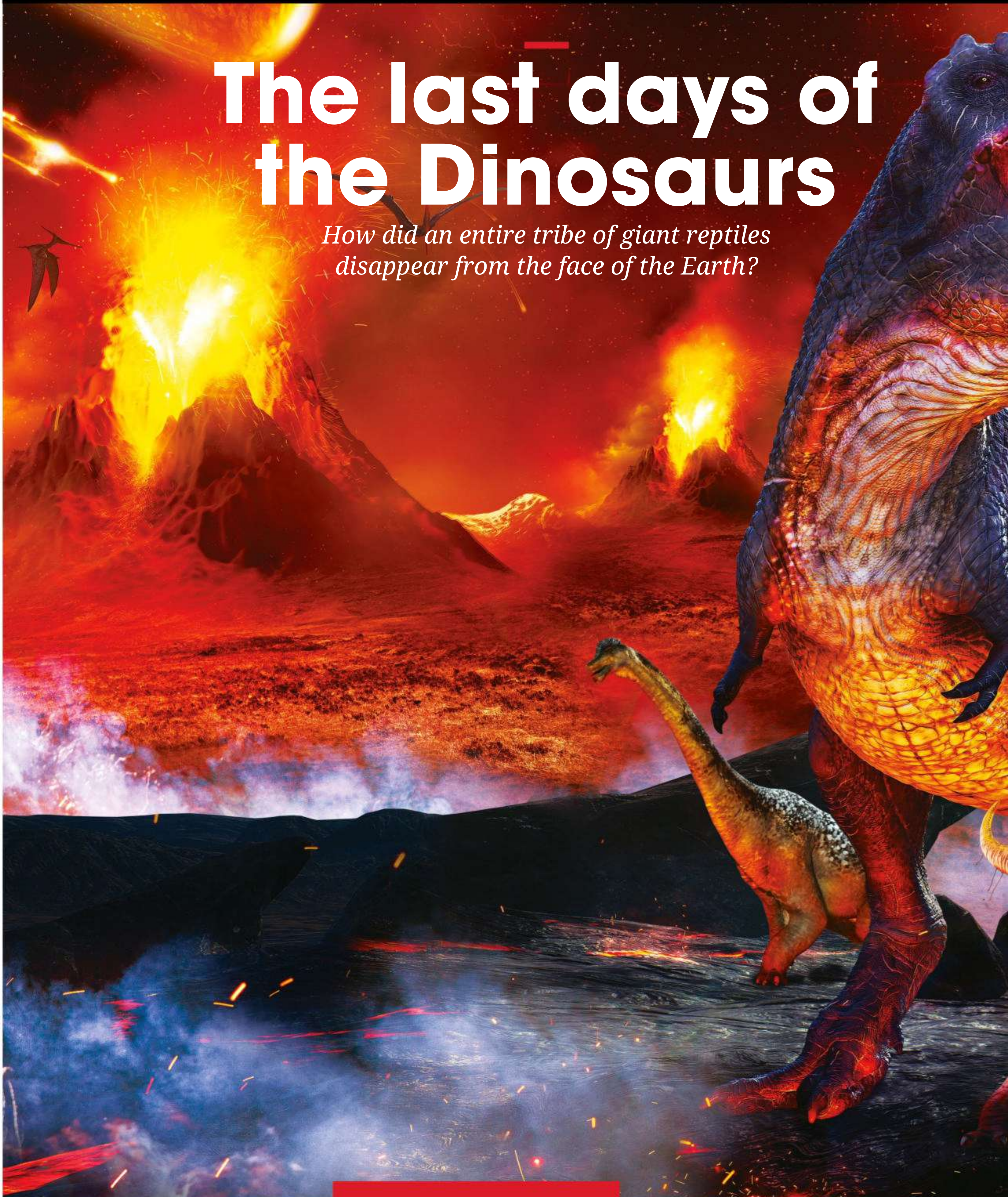


Feather imprints are clearly visible in well-preserved Archaeopteryx fossils such as this one

Extinction & Legacy

The last days of the Dinosaurs

How did an entire tribe of giant reptiles disappear from the face of the Earth?



Did you know?
Some scientists have posited another theory for the KT extinction – a prolonged period of volcanism

In 1677, English naturalist Robert Plot came face-to-face with a thigh bone belonging to an animal one and a half times his height. He thought the monstrous femur must have belonged to a giant. Since then, enormous bones have shown up in rocks around the world, but the creatures that they belonged to are nowhere to be seen.

From the spike-thumbed iguanodons of England to the feathered microraptors of China and the iconic tyrannosaurs of the United States, dinosaurs ruled every corner of our planet, but between 66-64 million years ago, they completely disappeared. The so-called K-T extinction marks the transition between the Cretaceous and Tertiary periods of geological history.

During this catastrophic period, almost three-quarters of life on Earth withered away. Ammonites and belemnites disappeared from the oceans, along with dozens of species of nanoplankton, two entire groups of clams and many of the relatives of modern starfish, sea urchins, brittle stars and sea cucumbers. The ocean's top predators, the mosasaurs, also vanished. Winged pterosaurs went missing from the skies, and flowering plants died in their thousands, leaving behind a landscape dominated by ferns.

In 1980, Nobel Prize-winning American physicist, Luis Alvarez, and his son Walter noticed something unusual in the geological record. At around the time of the KT extinction, there was a band of the brittle, white transition metal, iridium. Usually rarer than gold, spikes of this unusual element appear in more than 100 places across the globe. The most likely explanation was an asteroid impact.

Iridium might be rare on our planet, but it's common in space rock. If an asteroid had collided with Earth, it could have kicked the metal into the atmosphere. As the dust settled, this would have formed a band in the rocks, marking the time of the impact.

At the level of this band there is also evidence of shocked quartz; a type of rock with distinctive microscopic features that form under intense pressure. There are also spheres of glass, made when molten rock is thrown up into the atmosphere and solidifies before it falls back to the ground. And there are vast quantities of soot, which could signal large-scale forest fires caused by burning debris from an extraterrestrial impact. Traces of the asteroid are greatest in North America. In Haiti there is a thick band of clay filled with glass spheres, and in the Gulf of Mexico tumbled rocks hint at an enormous tsunami, which could have been caused by an asteroid slamming into the planet.

To cause this level of destruction, the asteroid would have had to have been more than ten kilometres wide and travelling so fast that it would have gouged a 100-kilometre-wide hole in the surface of the planet. It should have left an enormous crater, but the impact site was nowhere to be seen, and not everyone was convinced by the theory.

Earth was already undergoing a climate crisis; sea temperatures were rocking up and down, and water levels were rising and receding. What's more, asteroids aren't the only source of iridium, and extraterrestrial impacts aren't the only way that ash gets into the atmosphere. Even shocked quartz and glass spheres can be made by something other than an asteroid. All of these features could also be explained by volcanoes, and around the time the dinosaurs disappeared, there were some monumental eruptions.

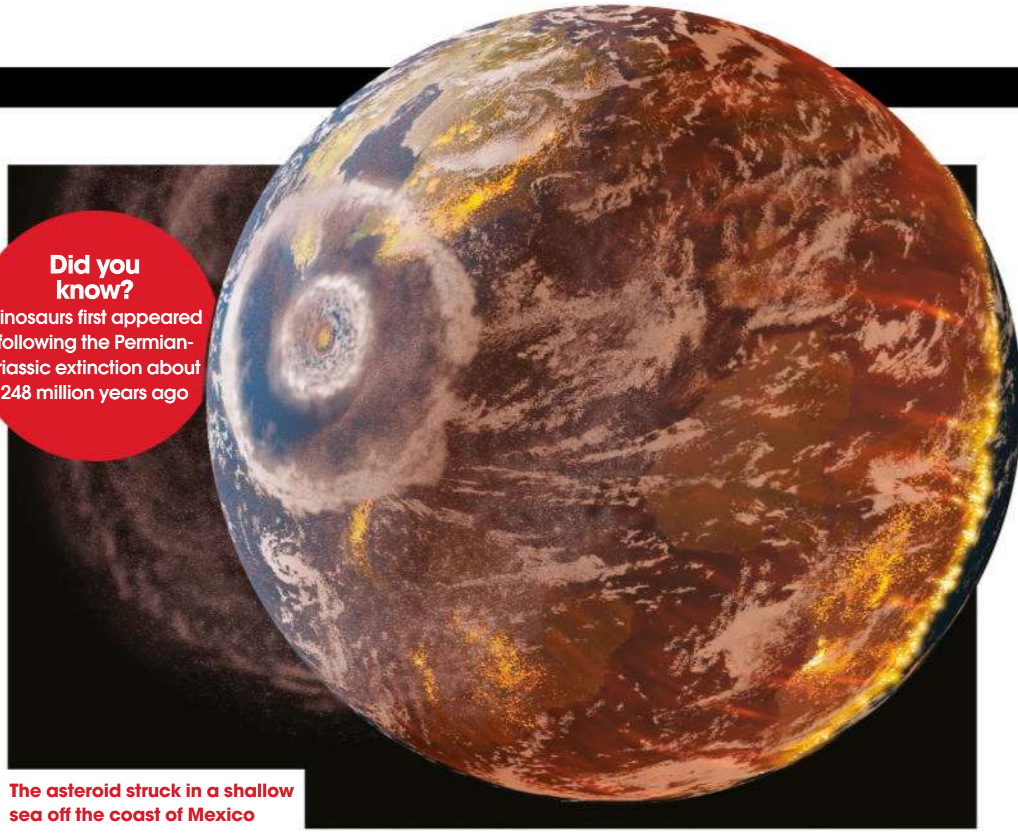
At that time, India was an island sitting on top of a volcanic hot spot. Bubbles of hot rock were rising from the Earth's mantle, which, unlike the crust, contains high levels of iridium. The magma poured out onto the surface, depositing more than 1 million cubic metres of new rock and forming vast lava plains now known as the Deccan Traps. As this happened, ash, sulphur and metal would have billowed and plumed into the air, potentially blocking out sunlight.

Both sides claimed the same evidence for their explanation of the trigger that caused the dinosaurs' demise, and without an actual impact crater, the Alvarez hypothesis had some gaps, but in 1990 geoscientist Alan Hildebrand found the smoking gun. Buried in a shallow sea off the coast of Mexico, there was a 180-kilometre-wide hole with strange gravity and an unusual magnetic field. It contained igneous rock, shocked quartz, spheres of glass and breccias – structures made from crushed rock glued together by mineral cement. It looked like the debris of an asteroid impact. From the shape of the crater, it appears the asteroid came in at an angle, skidding debris up towards North America. The rock would have been fractured by intense vibrations, shooting molten debris into the air, and the thermal shock would have been so intense that everything within sight of the impact would have been totally obliterated.

What followed would have been an earthquake of a magnitude unmatched by even the most powerful in recorded history. Vast tsunami waves would have been hurled across the oceans and debris from the impact site would have shot up with such force that some escaped the atmosphere. As the jettisoned rocks returned they would have burnt up, raining fire across the ground. Plants and animals in the surrounding area would have died instantly or within a matter of days.

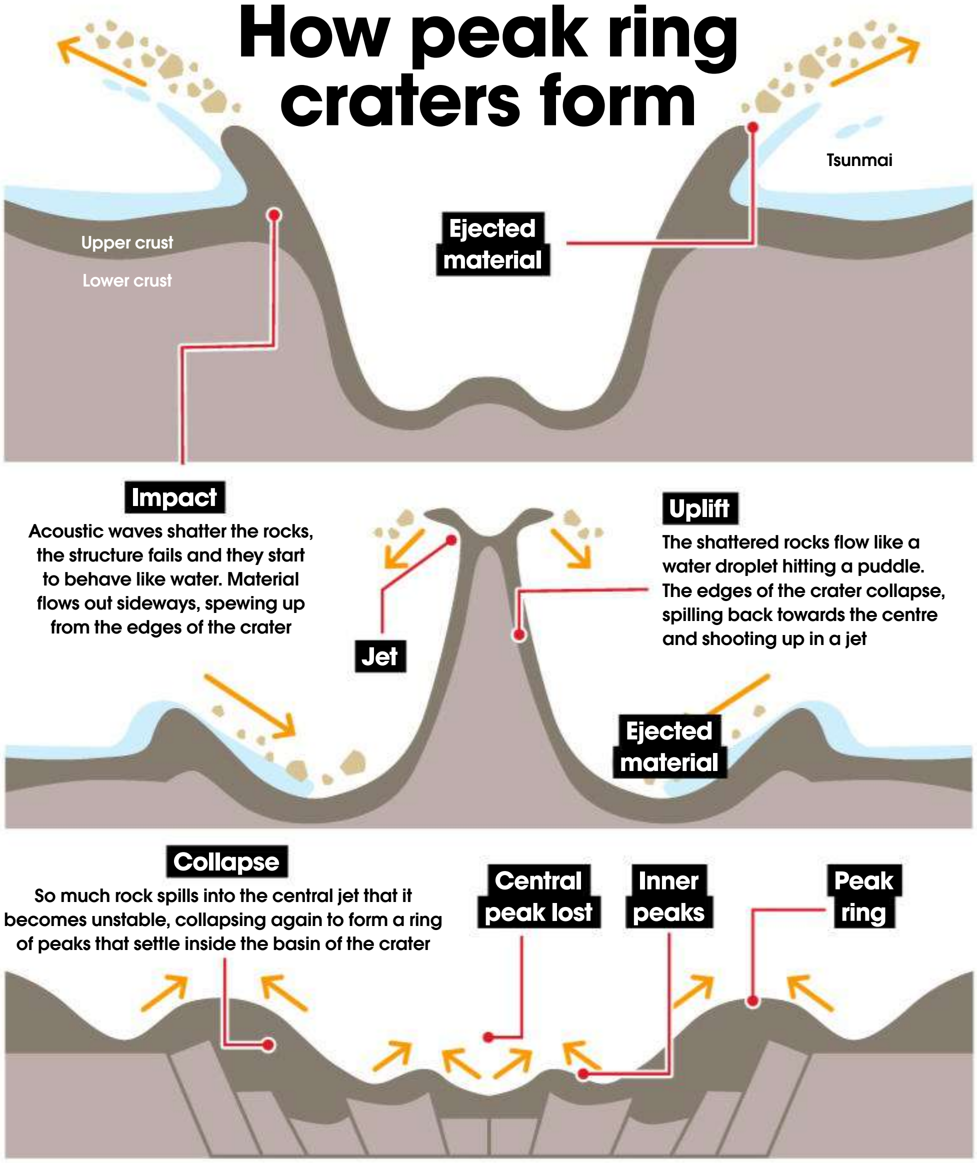
Later, as fragments of ash, sulphur and soot from burning forests clogged the air, the world

Did you know?
Dinosaurs first appeared following the Permian-Triassic extinction about 248 million years ago

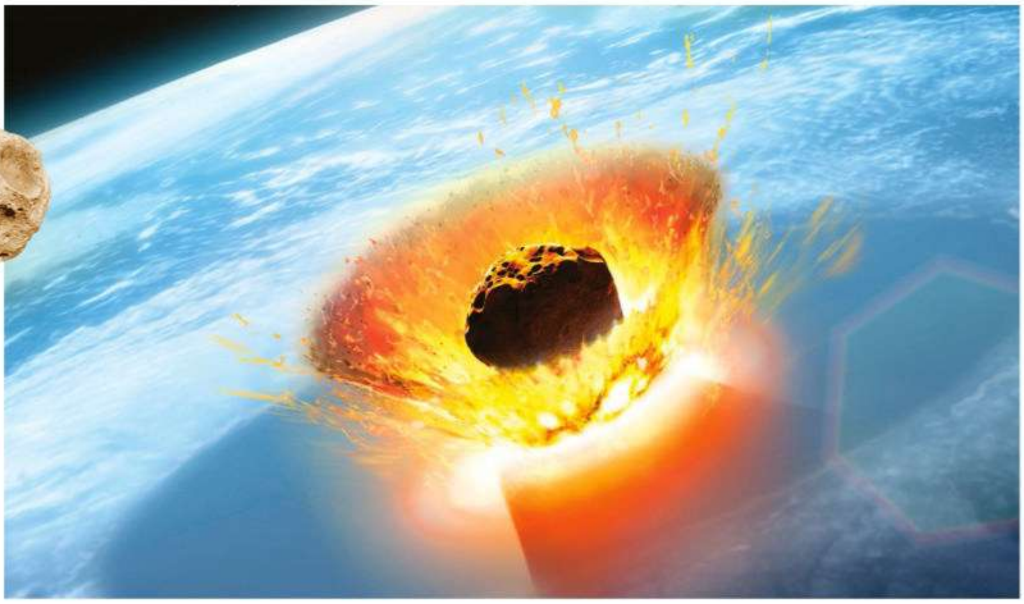


The asteroid struck in a shallow sea off the coast of Mexico

How peak ring craters form



The extinction in numbers



10km
The size of the asteroid

180km
The width of the Chicxulub crater

65-66 million
The number of years that have passed since the impact

11
The magnitude of the earthquake that would have shaken Earth after the impact

Biggest recorded quakes compared
9.5 Valdivia, Chile, 1990
9.2 Prince William Sound, Alaska, 1964
9.1 Sumatra, Indonesia, 2004
9.1 Sendai, Japan, 2011
9.0 Kamchatka, Russia, 1952

70%
The estimated proportion of species wiped out by the impact

10 degrees
The rise in global temperature following the impact

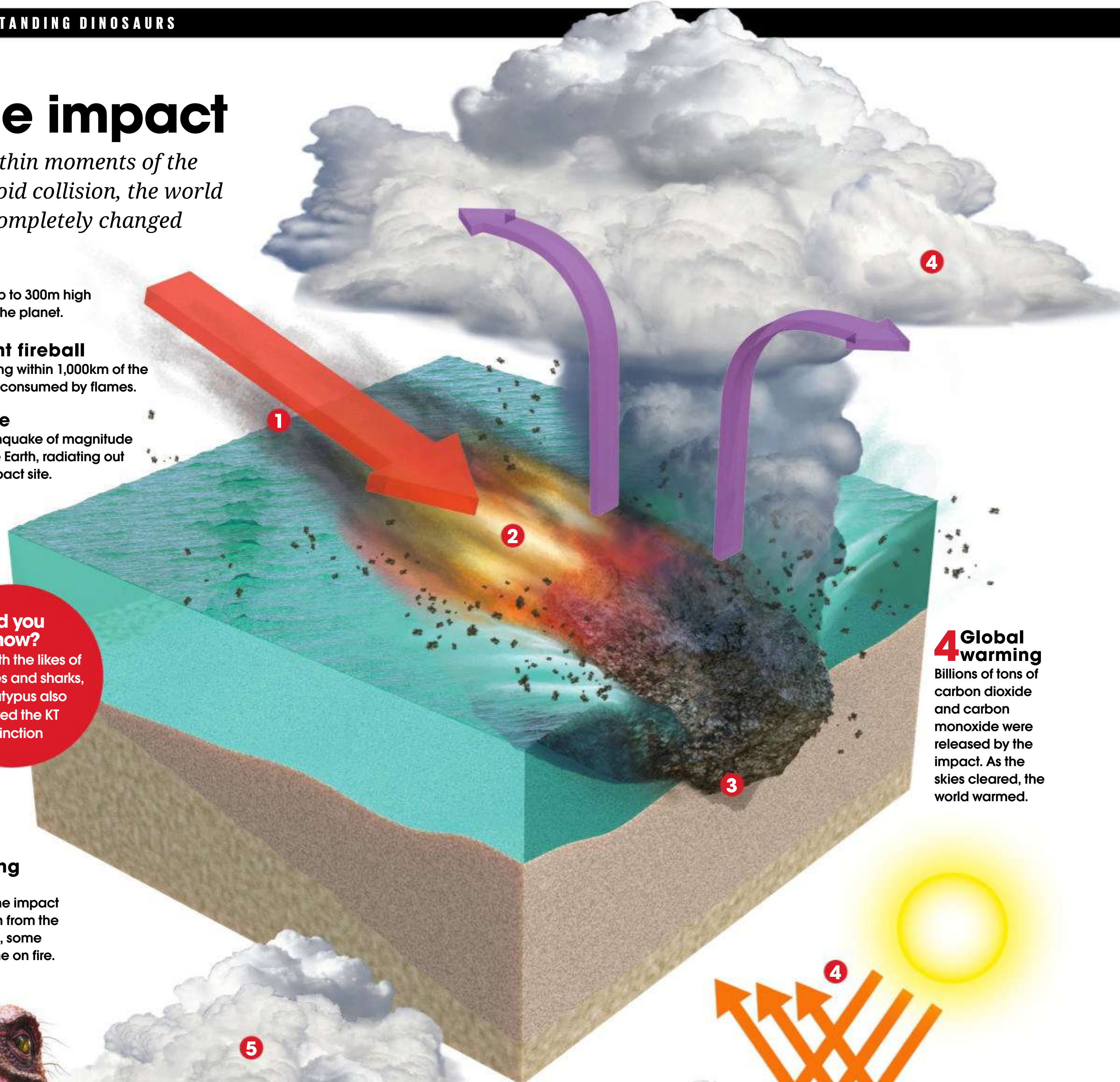
100 million megatons
The blast force of the impact

The asteroid came down in a shallow sea, triggering a massive tidal wave

Glass and rock rained from the sky over North America

The impact

Within moments of the asteroid collision, the world completely changed



1 Flood
Waves up to 300m high tore across the planet.

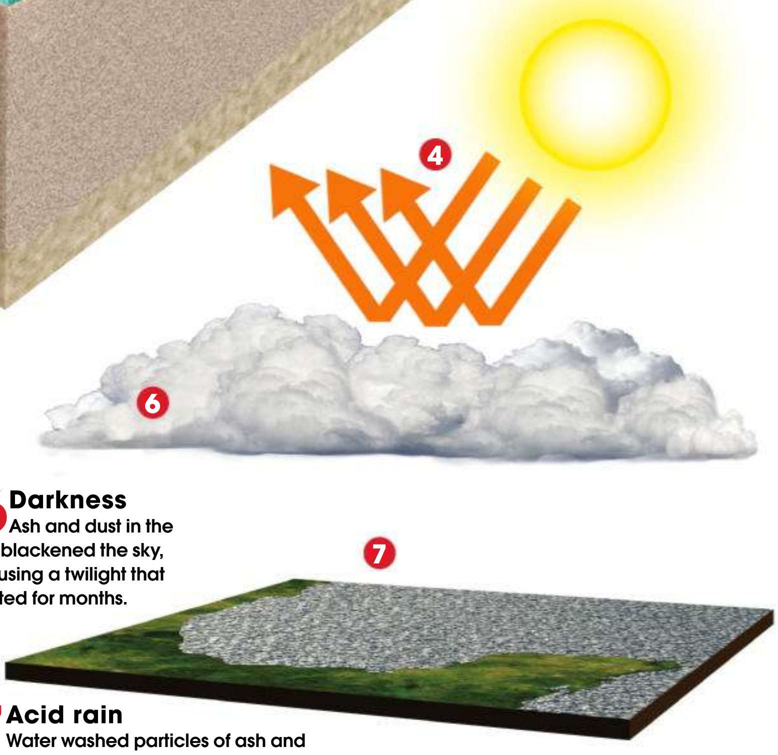
2 Instant fireball
Everything within 1,000km of the impact was consumed by flames.

3 Quake
An earthquake of magnitude 11 shook the Earth, radiating out from the impact site.

Did you know?
Along with the likes of crocodiles and sharks, the platypus also survived the KT extinction

4 Global warming
Billions of tons of carbon dioxide and carbon monoxide were released by the impact. As the skies cleared, the world warmed.

5 Raining rock
Rock from the impact rained down from the atmosphere, some molten, some on fire.



6 Darkness
Ash and dust in the air blackened the sky, causing a twilight that lasted for months.

7 Acid rain
Water washed particles of ash and sulphur out of the sky as acid rain.

would have been plunged into perpetual twilight for weeks or even months. This 'impact winter' would have hit photosynthesisers hard, knocking out plankton in the seas and plants on land. With the bottom falling out of the food chain, entire ecosystems would have started to feel the strain.

The dust poured out of the sky as acid rain, but the ordeal was not yet over. The Chicxulub crater, as it is now known, sits right in the middle of a three-kilometre-thick layer of carbonate rock. It acts as solid storage for greenhouse gases like carbon dioxide, and when struck, it could have sent temperatures spiralling. As the air finally cleared, billions of tons of these greenhouse gases would have triggered rampant global warming.

As Hildebrand said at the time of the discovery: "The Chicxulub impact, having presumably produced the largest impact crater on Earth, would have caused a mass extinction."

But even with the crater identified, some people still have their doubts. The most complete fossil record comes from North America, but even so, it's hard to create an exact timeline. Rock that old can't be carbon-dated, so it's not easy to tell if the dinosaurs all died at once, or if the extinction happened gradually. And not all species were preserved, so it's hard to piece together the ecosystem in enough detail to understand what caused it to fall apart. Specific conditions are needed to preserve the bones of fallen animals, and many perished without a trace.

Although there is good evidence that an asteroid did strike at Chicxulub, whether it killed the dinosaurs is hard to confirm. Some scientists argue that the impact happened about 300,000 years before the mass extinction, because some of the fossil evidence sits in layers of sediment above the impact line.

It's possible that this chunk of sediment was thrown on top of the rocks by tsunamis triggered by the asteroid, but it's also possible that the sediment was laid down gradually and that the

Incineration
Everything in the surrounding area was charred by an enormous fireball

Darkness falls
The debris blocked out sunlight, plunging the Earth into a lengthy period of darkness

Resurgence
As the dust cleared, surviving seeds and spores started to grow and animals emerged

What a difference a moment makes

The Chicxulub crater sits just off the coast of Mexico, in a shallow sea where the sediment was once filled with carbon and sulphur. When the asteroid struck, this rock shot into the atmosphere. 100 billion tons of sulphate particles and carbon – in the form of carbon dioxide, carbon monoxide and methane – entered the air. The sulphate first reflected the light, cooling the planet, but when it washed out of the sky as acid rain the carbon turned the atmosphere into a greenhouse and global temperatures climbed by degrees.

But a BBC documentary revealed that if the impact had come just seconds later, the rock would likely have settled in the depths of the ocean. Tsunami waves would still have flooded the surface, but the killer sulphur and greenhouse gases might never have entered the atmosphere and the dinosaurs may have been spared.

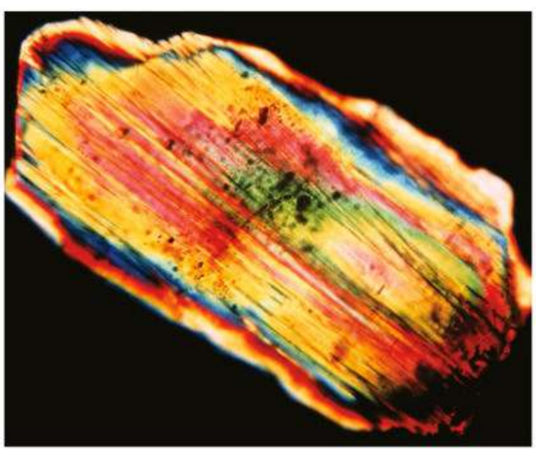
If the asteroid had come down in the deep ocean, the dinosaurs might have survived extinction of the dinosaurs wasn't as rapid as it might first appear. There's evidence that animals burrowed into the soft rock and there's erosion that looks like it was created by flowing water.

To dig deeper into the role of Chicxulub in the last days of the dinosaurs, scientists have been drilling into the remains of the impact site. Chicxulub is the largest impact crater on Earth. The asteroid that caused this hole was so big that it created a distinctive ring of molten and fragmented rock inside the outline of the crater – the so-called 'peak ring'. Since the impact the crater has been buried in 17 metres of water and 500 metres of limestone.

Between 2001 and 2002, the International Continental Drilling Program piled into the structure from the land in Mexico, revealing rock known as 'impact melt' that was likely made from fragments of rock that were shattered, spewed and then glued together when the crater formed. The drills also revealed evidence of hydrothermal activity caused by the huge impact, hinting that steam might have vented onto the crater for more than a million years after the asteroid struck.

In 2016, using a diamond-tipped drill, scientists bored into the structure again, this time targeting the peak ring to find out how it was formed and what happened in the aftermath. One startling discovery was the presence of pink granite in their drill samples. This crustal rock should have been down at a depth of 7,600 metres, but it turned up at 760 metres, evidence of the intense shock that crumpled and shook the Earth below.

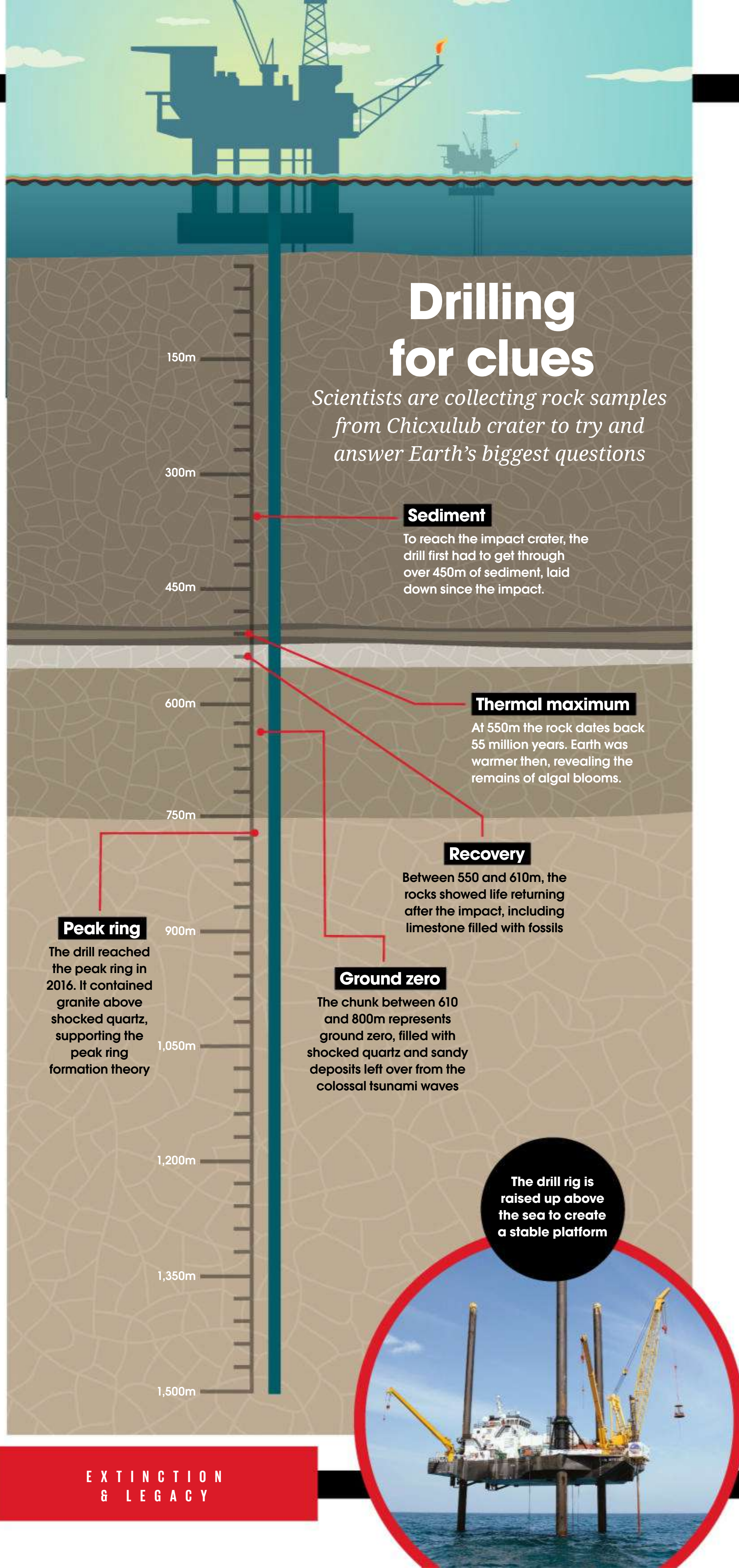
There are still many unanswered questions about the extinction of the dinosaurs, and the reality is that we won't ever know the truth of what happened for sure. The Chicxulub crater is thought to have spawned one of the most devastating extinction events of all time, but evidence being gathered from the remains of the crater hint that impacts can nurture life as well as destroy it.



The stress lines inside shocked quartz are caused by intense pressure

Drilling for clues

Scientists are collecting rock samples from Chicxulub crater to try and answer Earth's biggest questions



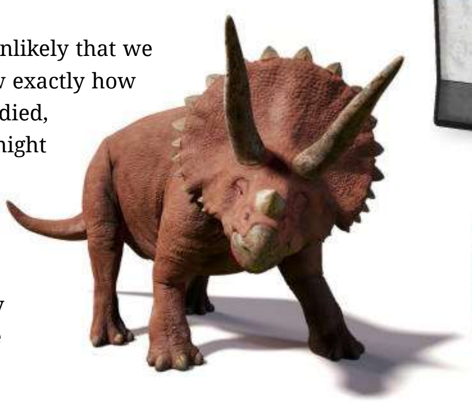
The drill rig is raised up above the sea to create a stable platform

Not only did the KT extinction make way for the rise of mammals; a 2020 study from a drilling expedition revealed a large network of channels that were filled with warm water after the impact. At first they would have been too hot for even the hardiest of life forms, but as they cooled, microscopic life could have thrived in the warm, damp cracks, nourished by minerals leaching out of the rocks. And this has exciting implications for the origins of all living things.

Though life was already firmly established by the time the Chicxulub asteroid arrived, the crater gives us a glimpse into the kinds of conditions that might have been present on the ancient, lifeless Earth. Charles Darwin thought that life might have begun in a "warm little pond", where minerals mixed with water and organic molecules. Asteroids are stuffed with organic compounds that could have provided the ingredients for the chemistry life to begin, and if they set up warm, wet, mineral-rich niches when they strike the Earth, they could be the parents of Darwin's little ponds.

In 2020, NASA's OSIRIS-REx spacecraft reached the asteroid Bennu to collect samples (which were returned to Earth in 2023), in search of clues as to whether asteroids could have helped life to begin on Earth billions of years before the dinosaurs even existed.

While it is unlikely that we will ever know exactly how the dinosaurs died, their demise might shed light on an even bigger question – how did they get here in the first place?



Mass extinctions

The KT extinction was not the first and it won't be the last

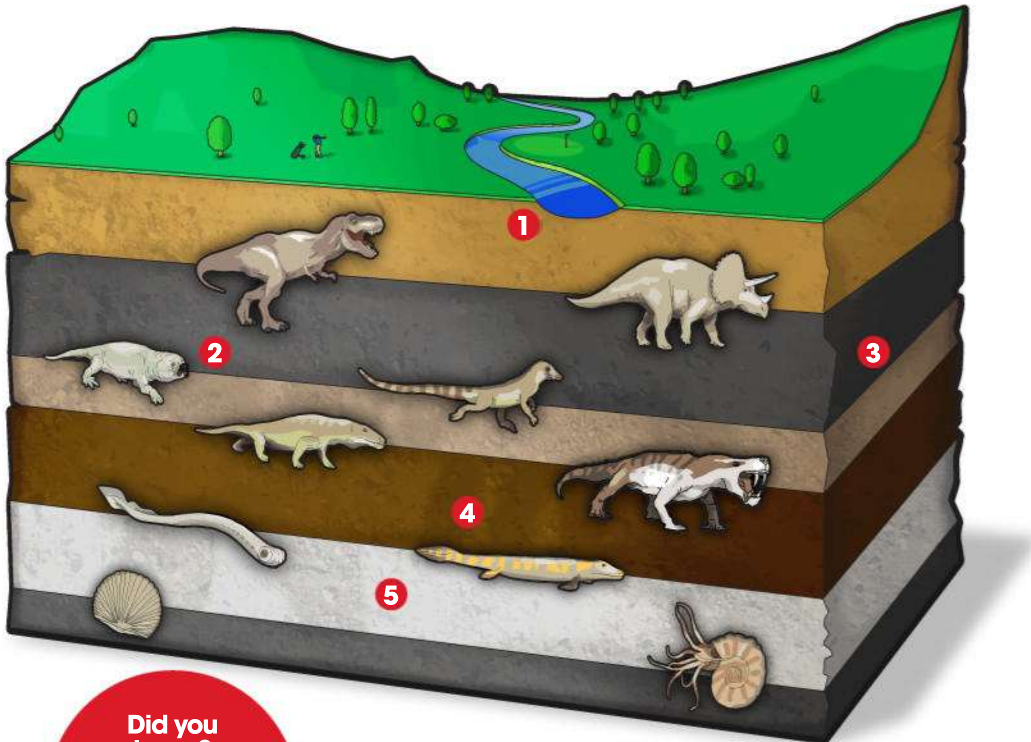
1
66 MYA
Cretaceous-Tertiary
70% of species were killed, including dinosaurs, ammonites and pterosaurs.

2
248 MYA
Permian
Also known as the 'Great Dying', this devastating event killed 96% of all species.

3
200 MYA
Triassic-Jurassic
Half of all species expired, including significant numbers of marine animals.

4
359 MYA
Late Devonian
75% of all species succumbed, including reefs and shallow sea creatures.

5
443 MYA
Ordovician-Silurian
85% of life disappeared, most of which was in the sea.



Did you know?
In 1824, William Buckland became the first person to describe a dinosaur when he named the megalosaurus

> **"Microbes may have thrived, nourished by minerals leaching out of the rocks"**

Making way for mammals

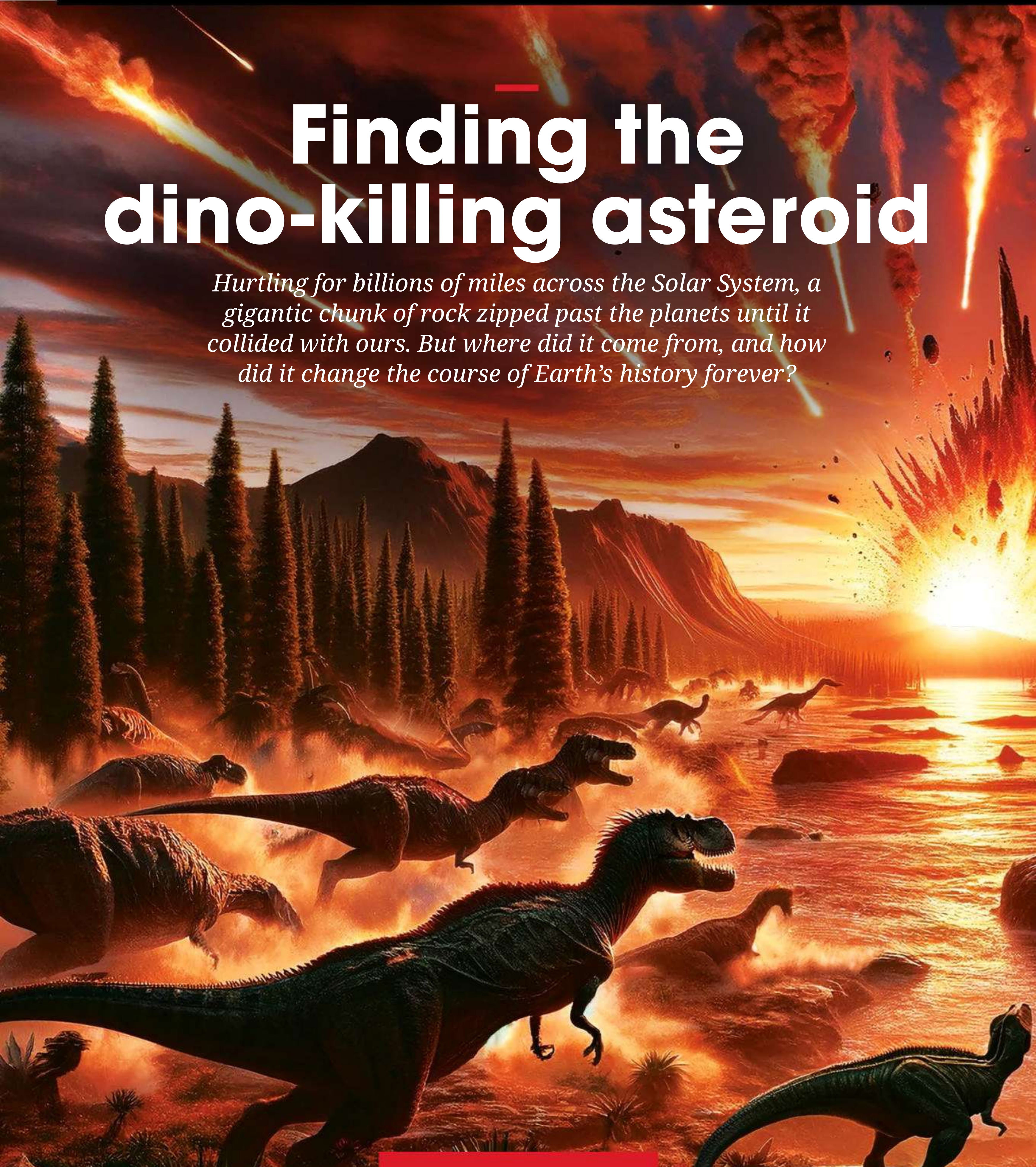
The KT extinction event devastated the Earth, but without it, we wouldn't be here today. As the dominant land animals struggled to survive in a world charred by debris, blackened by sulphur and soot and heated by greenhouse gases, tiny mammals were shielded in their burrows. Many birds, reptiles and amphibians were also spared; saved by their small body size and flexible, often insect-based, diets. Some freshwater species also fared well; their food chain includes detritus – nutrients released by decomposition – which washes into streams and lakes, providing a steady supply of fuel.

As Earth started to recover there were gaps in the food chain for these animals to fill and the survivors spread out to take the places of the dinosaurs. Over time they evolved to become the huge variety of species that we see today.

Small animals including mammals survived the KT extinction

Finding the dino-killing asteroid

Hurtling for billions of miles across the Solar System, a gigantic chunk of rock zipped past the planets until it collided with ours. But where did it come from, and how did it change the course of Earth's history forever?



EXTINCTION & LEGACY

Did you know?
Carbonaceous chondrites make up five per cent of all meteorites collected

Around 66 million years ago, life on Earth was thriving. The Cretaceous period culminated in land covered in lush forests rich with biodiversity, including giant dinosaurs. Casting your eyes over the Cretaceous forests, you might have seen the heads of Titanosaurs poking over the canopy, apex predators such as Tyrannosaurus rex chasing prey and the last flying reptiles, Pterosaurs, soaring in the sky. However, the dominion of the dinosaurs was brought to an abrupt end when a mountain-sized asteroid tore through Earth's atmosphere and crashed into the ocean. In mere

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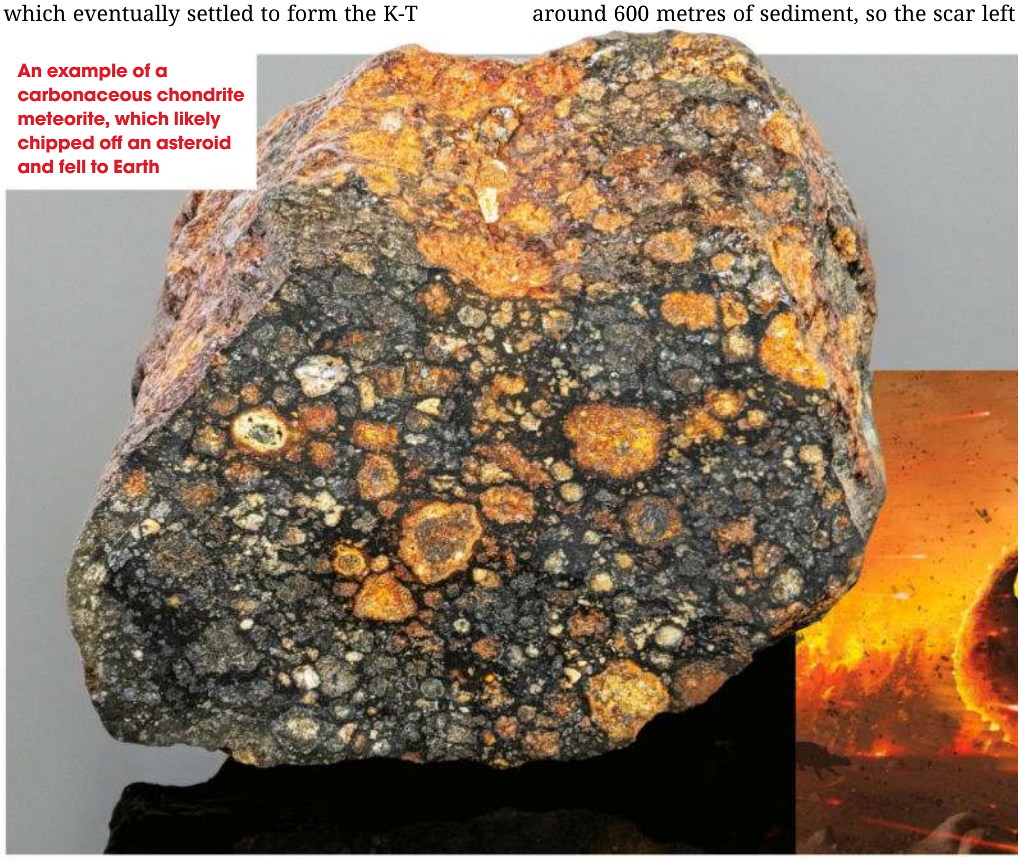
moments, the fireball would have appeared in the sky and burned brighter than the Sun as it hurtled towards its eventual impact site in the Gulf of Mexico, known as the Chicxulub crater.

Most asteroids in our Solar System can be found orbiting the Sun between Mars and Jupiter in a region known as the asteroid belt. It's estimated that there are up to 1.9 million asteroids almost a mile in diameter that reside here. As remnants of the Solar System's formation 4.6 billion years ago, the asteroid belt is where the leftovers of these planet-building 'bricks' have fallen into orbit around the Sun. Occasionally, these space rocks are knocked by the gravitational pull of passing planets and flung out into other parts of the Solar System. Scientists have long speculated that the dino-killing asteroid originated in the asteroid belt and may have been subject to a similar gravitational catapulting. However, in 2024, researchers from the University of Cologne in Germany confirmed that the Chicxulub impactor's origin is far beyond the asteroid belt.

Their conclusions were drawn from analysing the chemical composition of a thin layer of sediment found throughout the world's bedrock, called the Cretaceous-Paleogene boundary (K-T boundary). In the aftermath of the asteroid impact, rock, ash and dust were ejected into the atmosphere, which eventually settled to form the K-T boundary. Within the boundary are elements rarely found on Earth, but commonly found on asteroids and meteorites. One of these elements is ruthenium. After comparing the ruthenium in the K-T boundary with ruthenium from other prehistoric impacts – some dating as far back as 3.5 billion years ago – the researchers concluded that the asteroid that killed the dinosaurs had the characteristics of a carbon-rich type of asteroid called a carbonaceous chondrite. This type of asteroid is fragile and formed beyond the orbit of Jupiter during the birth of the Solar System.

As to what sent the killer asteroid hurtling towards our planet, scientists may never know for sure. However, it's thought that like many other asteroid impacts, a gravitational swing from another planet or a collision with another rocky object may have sent the Chicxulub asteroid on a one-way trip to Earth. Landing in the shallow ocean just north of the Yucatán Peninsula, Mexico, the impact of this trillion-tonne rock penetrated deep into Earth's crust, churning up solid rock to carve out a crater around 100 miles wide. The asteroid hit the surface at a speed of around 12 miles per second and was vaporised into plasma, molten rock, rubble and dust in a fraction of a second.

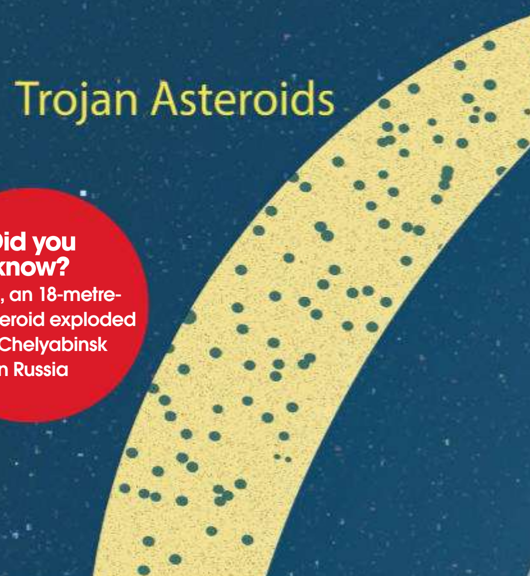
Today it's buried underwater beneath around 600 metres of sediment, so the scar left



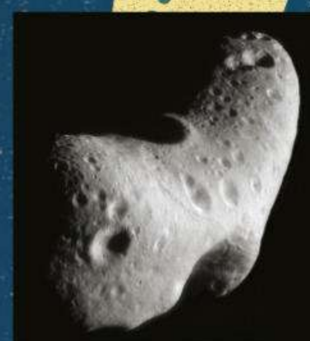
An example of a carbonaceous chondrite meteorite, which likely chipped off an asteroid and fell to Earth

Outer origins

There are countless asteroids in the inner Solar System, but the Chicxulub impactor came from farther afield

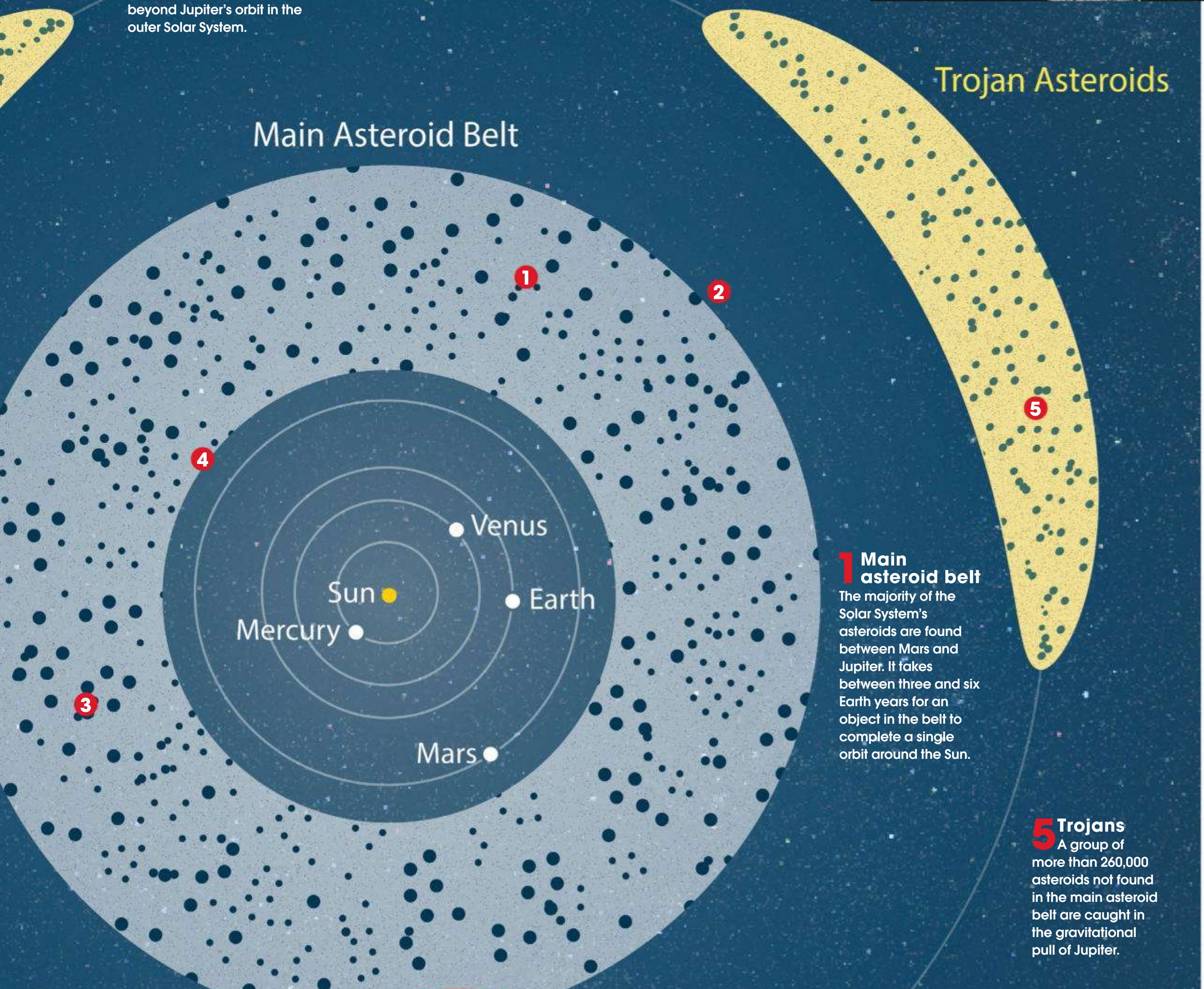


Did you know?
In 2013, an 18-metre-wide asteroid exploded over Chelyabinsk in Russia



4 Inner asteroids
Siliceous, or 'S-type', asteroids dominate the inner region of the asteroid belt and make up around 17 per cent of known asteroids.

The force of the impact was around 4.5 billion times the explosive power of the Hiroshima atomic bomb



2 Outer edges
Around 75 per cent of asteroids are coal-black 'C-type' carbon asteroids that are mostly found in the outer regions of the belt, farthest away from the Sun.

6 Dino killer
Although the exact origin of the dino-killing asteroid remains unknown, researchers have estimated that it emerged from beyond Jupiter's orbit in the outer Solar System.

1 Main asteroid belt
The majority of the Solar System's asteroids are found between Mars and Jupiter. It takes between three and six Earth years for an object in the belt to complete a single orbit around the Sun.

5 Trojans
A group of more than 260,000 asteroids not found in the main asteroid belt are caught in the gravitational pull of Jupiter.

3 In the middle
'M-type', or metallic, asteroids are packed with nickel and iron and are mostly found orbiting in the middle of the asteroid belt.

"A collision with another rocky object may have sent the Chicxulub asteroid on a one-way trip to Earth"

7 Melt sheet
The power of the impact generated enough heat and pressure to create a sheet of molten bedrock in the crater.

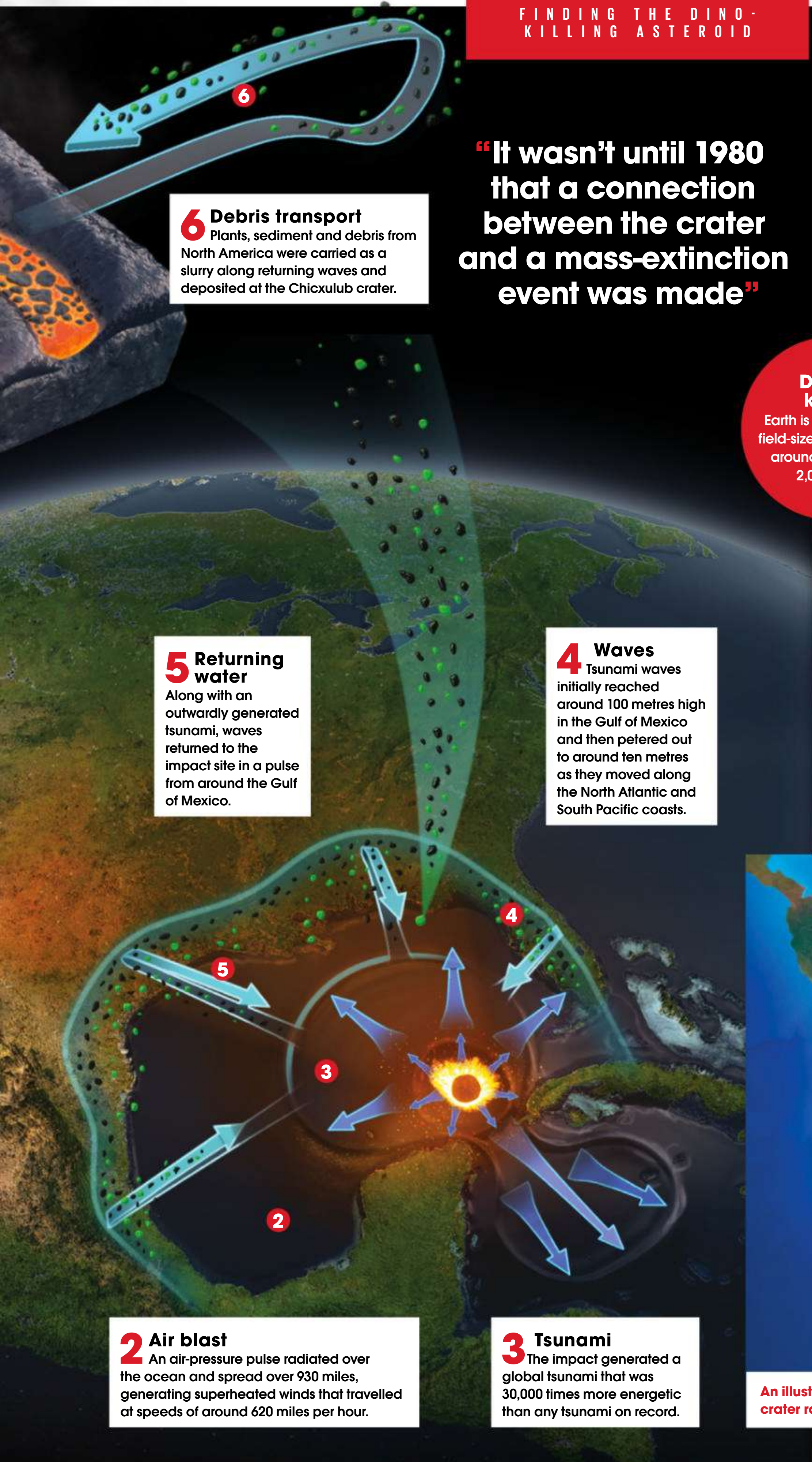
Earth strike

The first hours of the impact involved a series of cataclysmic events

1 Impact
Upon impact, the asteroid released the same energy as around 100 trillion tonnes of TNT.

Did you know?
The Chicxulub meteorite travelled at 58 times the speed of sound

Before the world was set ablaze by a fireball, the Cretaceous period was filled with green, luscious forests and countless creatures



"It wasn't until 1980 that a connection between the crater and a mass-extinction event was made"

by the impact was only discovered in the 1960s by scientists who were searching for oil. However, it wasn't until 1980 that a connection between the crater and a mass-extinction event was made by Nobel prize-winning physicist Luis Alvarez and his geologist son Walter Alvarez. The duo discovered around 160 times the normal amount of iridium, an element typically found in asteroids and meteorites, at the crater site. During the 1990s, the structure of the crater's walls was confirmed, and it was dubbed the Chicxulub crater after the nearby town of Chicxulub Pueblo.

Did you know?
Earth is hit by football field-sized 'meteoroids' around once every 2,000 years

The Chicxulub crater is unique as Earth's only crater with a well-preserved 'peak ring', which is around 56 miles wide. If an impact is large enough, a secondary interior ring of rocky peaks forms inside the perimeter of the crater. This nine-metre-thick peak ring was formed within ten minutes of the impact. Much like the rippling movement of water when a stone is dropped into a pond, when an asteroid hits the ground it lifts up, surges outwards and rebounds like liquid to form a peak ring and the crater's outer ring.

The consequences of the collision were devastating and far-reaching. Around 75 per cent of species were lost as a result of the impact, including up to around 1,000 non-


An illustration of the rings of the Chicxulub crater raised to the surface

© Illustration by Nicholas Forder / Getty

Crater cousins

Around 248 miles off the coast of West Africa is an underwater crater that may have been created at the same time the dino-killing asteroid landed on Earth. Known as the Nadir crater, this five-mile-wide geological feature sits beneath 300 metres of seafloor sediment. The discovery was made by researchers from Heriot-Watt University in Scotland, who were surveying the geology off the coast of Guinea. "These surveys are kind of like an ultrasound of Earth. I've spent probably the last 20 years interpreting them, but I've never seen anything like this," Dr Uisdean Nicholson said at the time. After studying fossil fragments, researchers dated the impact to around 66 million years ago. Like its dino-killing cousin, this asteroid is also thought to have generated an enormous tsunami wave around 1,000 metres high. The meteorite that created this crater may have been a piece that separated from the main body of the Chicxulub asteroid and landed thousands of miles from the Gulf of Mexico – though it could have been a second separate impact.

Did you know?
Most rocks smaller than 25 metres burn up when they enter Earth's atmosphere

The Chicxulub asteroid may have had a friend that hit Earth at the same time

avian dinosaur species. The sheer force of the asteroid impact brought about a period of wildfires, dust clouds and darkness – a perfect storm for the downfall of the dinosaurs. Even the angle at which the asteroid entered Earth's atmosphere contributed to their extinction. In 2010, researchers from Imperial College London revealed that the angle at which the asteroid hit Earth was around 60 degrees above the horizon. This was "the worst-case scenario for the lethality on impact because it put more hazardous debris into the upper atmosphere and scattered it everywhere," said lead researcher Professor Gareth Collins.

The ejected debris and dust triggered what is often referred to as an 'impact winter'. By blocking out the Sun's light, the debris plunged the world into darkness, starving the world's plants in the process. Without the ability to photosynthesise, plant species withered away, cutting off the food supply to animals at the bottom of the global food chain and causing a knock-on effect that ultimately wiped out the majority of life on Earth.

Along with plunging the forests into dusty darkness, the asteroid impact also poisoned Earth's waterways. After a global tsunami rippled across the world's oceans, the sulphur that was released into the atmosphere following the impact acidified the oceans. Research has found that within 1,000 years of the impact, the pH of surface seawater fell by 0.25 units. During the same time frame, the levels of photosynthesis carried out by aquatic organisms dropped by half. It took around 40,000 years for the ocean pH level to return to normal.

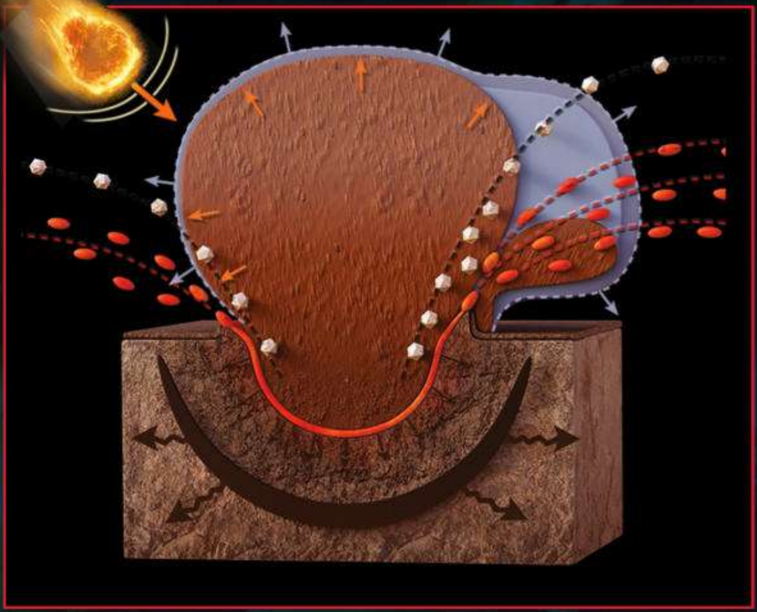
However, the asteroid might not have been solely to blame for the demise of the dinosaurs. Long before Earth was shaken by the impact, it was experiencing a period of climate change as a result of excessive volcanic activity in the Deccan Traps in what is now modern-day India. Around 300,000 years before the Chicxulub impact, the Deccan Traps had been throwing up around 10.4 trillion tonnes of carbon dioxide and around 9.3 trillion tonnes of sulphur into the atmosphere. Researchers have speculated that these volcanic emissions and the impact winter caused by the Chicxulub asteroid may have been the perfect cocktail of chaos to drive the dinosaurs to extinction.

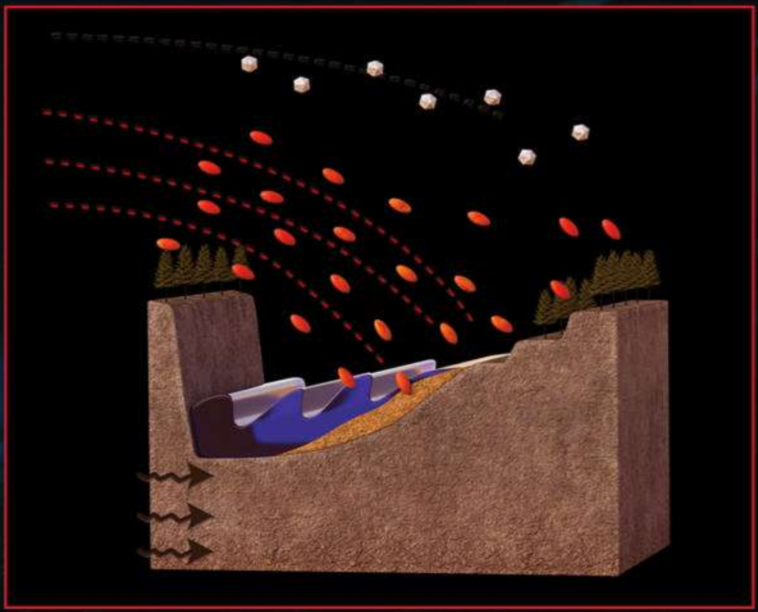
"The asteroid might not have been solely to blame for the demise of the dinosaurs"

A section of the five-centimetre-thick K-T boundary in Spain

Initiating an impact winter

How an asteroid hitting Earth caused countless animals to perish





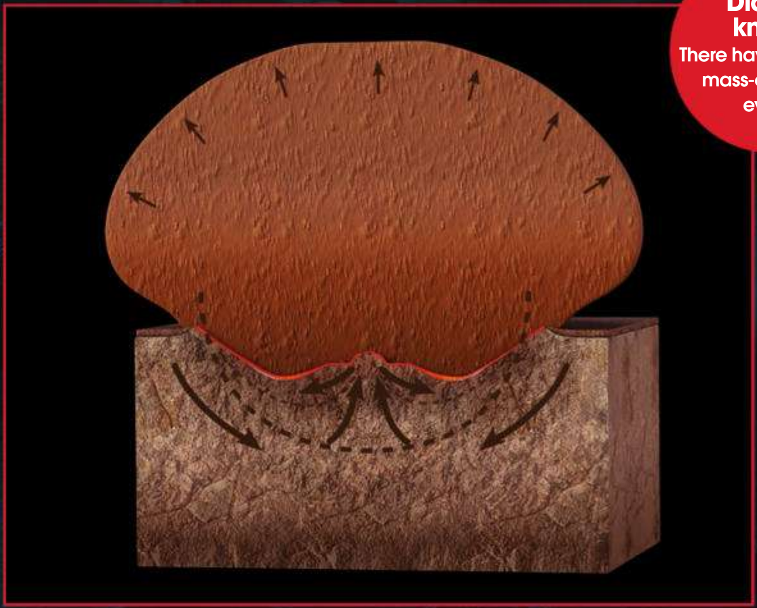
1 Initial collision

Within 20 seconds of the impact, the asteroid smashed up to 19 miles into Earth's crust. The collision incinerated everything within a 1,000-mile radius and ejected a plume of molten material amounting to around 25 trillion tonnes. Some of the smaller pieces of molten ejecta, known as spherules, were shot 40 miles up into the air before crashing back to the surface.

2 Release

Within the first five minutes of the impact, plumes of fine-particle material entered the atmosphere. Composed of around 75 per cent dust, another 24 per cent was sulphur and one per cent soot. Several hundred billion tonnes of carbon dioxide, sulphur dioxide and water vapour released by the vaporised rock were also ejected.

Did you know?
There have been five mass-extinction events



3 Blackouts and fires

The dust and gas acted as a curtain of smog, blocking the Sun's light from reaching Earth's surface. The dust debris is estimated to have persisted in the atmosphere for 15 years, contributing to global temperatures falling by 15 degrees Celsius. Each ejected spherule also acted as a small torch, igniting wildfires in around 70 per cent of the world's forests.

4 Death

While dinosaurs near the impact were certainly killed instantly, those farther afield likely died of starvation. It's estimated that the global blackout halted photosynthesis for around two years – enough time to cause the extinction of not only plant species, but also the animals that ate them. As a consequence, the predators that feasted on these herbivores met the same fate.

Othniel Marsh and his assistants were armed with guns at their digs to fend off hostile and aggressive competitors

The Bone Wars

The bitter feud between two 19th-century fossil hunters that spurred some of history's most significant dinosaur discoveries

The American Old West is famed for its duels and blood feuds. However, for palaeontologists, this era conjures up one image above all: the bitter rivalry between two of America's greatest fossil hunters, Othniel Charles Marsh and Edward Drinker Cope. Known as the 'Bone Wars', the competition between these oversized egos stretched from the 1870s well into the 1890s and led to the discovery of hundreds of dinosaurs. However, it also involved bribery, theft, the destruction of evidence, and both the figurative and literal throwing of stones.

Edward Drinker Cope was born in 1840 in Philadelphia, Pennsylvania, to wealthy Quaker parents, Alfred and Hanna. While working part-time at the state's Academy of Natural Sciences, Cope published his first scientific paper in 1859, still only 19 years old. He also studied, catalogued and even reclassified a number of the academy's specimens. His passion for science led him to learn French and German so that he could read the latest natural history research. In 1863, possibly to escape the draft for the American Civil War, Cope went one step further and travelled to western Europe, which was at the forefront of palaeontology research at the time. It was here that he first met Othniel Charles Marsh.

Marsh was Cope's polar opposite. Born in 1831 in Lockport, in upstate New York, his family was comparatively poor. However, he did have a rich uncle, George Peabody, who paid for him to go the Philips Academy and later Yale University, from where he graduated in 1860. When the two men met at the University of Berlin, Marsh had two degrees under his belt, while Cope had little formal schooling beyond the age of 16.

However, while Cope had published 37 papers, Marsh's tally stood at a relatively measly two. Cope was impulsive, sometimes rash and tempestuous, in the way he approached his work, while Marsh trusted in a colder, more calculated methodology in his research. The pair even diverged on ideological lines: Marsh embraced Charles Darwin's relatively new theory of natural selection, while Cope ardently advocated a theory of evolution called Neo-Lamarckism.

It's likely Marsh considered Cope a bit of a dilettante, not really serious about paleontology, while Cope saw Marsh as too rough and uncouth to be a true scientist. What they had in common, though, was their unbridled sense of self-worth and a drive to stop at nothing to succeed.

Perhaps due to this shared zeal, they struck up a professional friendship. Over the next few years, they exchanged ideas, scientific manuscripts and even helped each other study and name fossils they found and received. But this amicable relationship took a sudden sour turn shortly after their return to the US.

In 1868, Marsh noticed an embarrassing flaw with one of Cope's largest finds thus far, a near-complete specimen of the aquatic Elasmosaurus. Noticing Cope had placed the head of the plesiosaur at the tail-end of the skeleton, he called on renowned expert Joseph Leidy — one of the mid-19th-century's most influential palaeontologists and former mentor to them both — to back him up.

Unfortunately, Cope had already published his findings by the time he accepted the mistake and, despite his desperate attempts to buy up every copy of the paper, several remained out of reach. Marsh and Leidy both managed to keep hold of their copies, prompting one of them (accounts vary on who) to cruelly highlight Cope's humiliating mistake at his next society meeting.

Worse still, around the same time, Marsh went behind Cope's back in making an agreement with Cope's long-time collaborator, marl pit owner Albert Vorhees. Marsh paid the excavators to send any interesting finds to him, rather than to Cope. The time of collaboration was over. A friendship forged in mutual ambition would soon turn into a personal rivalry of prehistoric proportions.

It started as an academic war of words. Cope, incensed at Marsh publicly humiliating him, rushed to publish any findings he made in the field in the hope of gaining the upper hand by virtue of volume. At first, these revolved mainly about a series of ancient mammals and reptiles. However, Marsh's superior academic status gave him the strength to override any studies Cope had made, leading to Edward's frustrations mounting even further. On top of that, Marsh's Yale funding and powers of persuasion meant Cope was considered persona non grata at many of the dig sites Marsh explored over this period.

Cope did manage to get some retribution in the form of a general reclassification of Eocene mammals, where he substituted Marsh's genera for his own, more broad-reaching classification.

The Bone Wars kicked into a high gear in the mountains above the tiny town of Morrison, Colorado, in 1877. Schoolteacher Arthur Lakes had come across a large deposit of colossal bones in the fossil-rich sandstone and decided to not only notify Marsh of the finding, but also to send him some 680 kilograms of fossilised

The age of dinosaurs depicted in a Victorian magazine

Evolution of antagonism

The clash between Cope and Marsh quickly developed beyond a war of words

1868

The backstabbing begins

Marsh bribes the New Jersey marl pit managers Cope usually works with to send their future fossil finds to him at Yale instead.

1871

Frontier prospecting

Both men go west to dig for fossils. Believing he has the greater claim because he arrived first, Marsh hires spies to track Cope's movements in Wyoming.

1873

Scientific snipping

Marsh and Cope attack each other's findings in scientific journals, quibbling findings and questioning who discovered species first.

1878

Trench warfare

The professors' teams in Wyoming and Colorado openly fight one another as well as destroy unwanted fossils to keep them out of rival hands.

1890

Public scandal

When Congress investigate the US Geological Survey, Cope recruits employees to testify against Marsh and also went to the newspapers. The public quarrel lost both men credibility.

1897

Extinction event

Even in death, Cope refused accept defeat. He donated his body to science on the condition that the size of his brain is compared to Marsh's. Marsh declined.

bones. For some reason, however, possibly due to a delayed response from Marsh, Lakes also sent a cache of fossils to Cope. Marsh soon found out, and rushed to publish his findings in the American Journal of Science ahead of Cope. Lakes wrote to Cope requesting he forwarded his bones on to Marsh.

Of course, Cope took this as a grievous insult and it only spurred him into further action.

Shortly after, Cope received correspondence from neighbouring Canon City in Colorado and subsequently discovered bones from gigantic herbivores, dinosaurs larger than any Marsh had described so far — a point of great pride to Cope. Marsh, not one to be outdone, ordered a quarry to be set up as close as possible to Cope's dig, but after a fruitless pursuit of superior fossils there, and a near-fatal accident for Marsh's assistants in Morrison, he took his battalion of dinosaur hunters elsewhere — Como Bluff, Wyoming.

As the Transcontinental Railroad was being built through remote parts of Wyoming, news spread of rich fossil fields in the area. Marsh was the first to take advantage, quickly striking deals with teams of explorers and workers to make sure they wouldn't turn to Cope.

The results from these digs would turn out to be history-defining; among the finds in Como Bluff were fossils of what would become some of the most famous dinosaur species in history. These included Stegosaurus, Allosaurus and Apatosaurus, among a number of other notable finds.

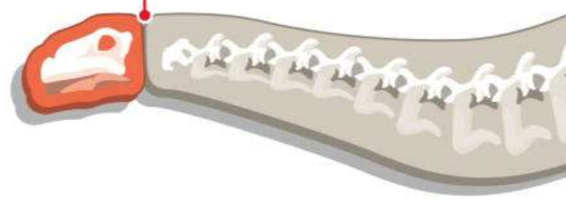
Having been beaten to the punch yet again, Cope now resorted to desperate tactics. Sending 'dinosaur rustlers' to the area, he attempted to covertly steal fossils from Marsh's site.

After one of Marsh's main expedition leaders, Carlin, decided to defect over to Cope's site, things quickly took an ugly turn. On top of rapidly expanding digs, often conducted haphazardly, resulting in regular irreparable damage to invaluable fossils, hostilities between the camps escalated dangerously.

The teams would regularly sabotage each other's camps and dig sites, and small skirmishes would break out, with men throwing rocks at each other. Explosives were even used to destroy used dig sites in order to prevent the 'enemy' from making potential further discoveries; little regard was paid to smaller fossils by this point.

Wrong head

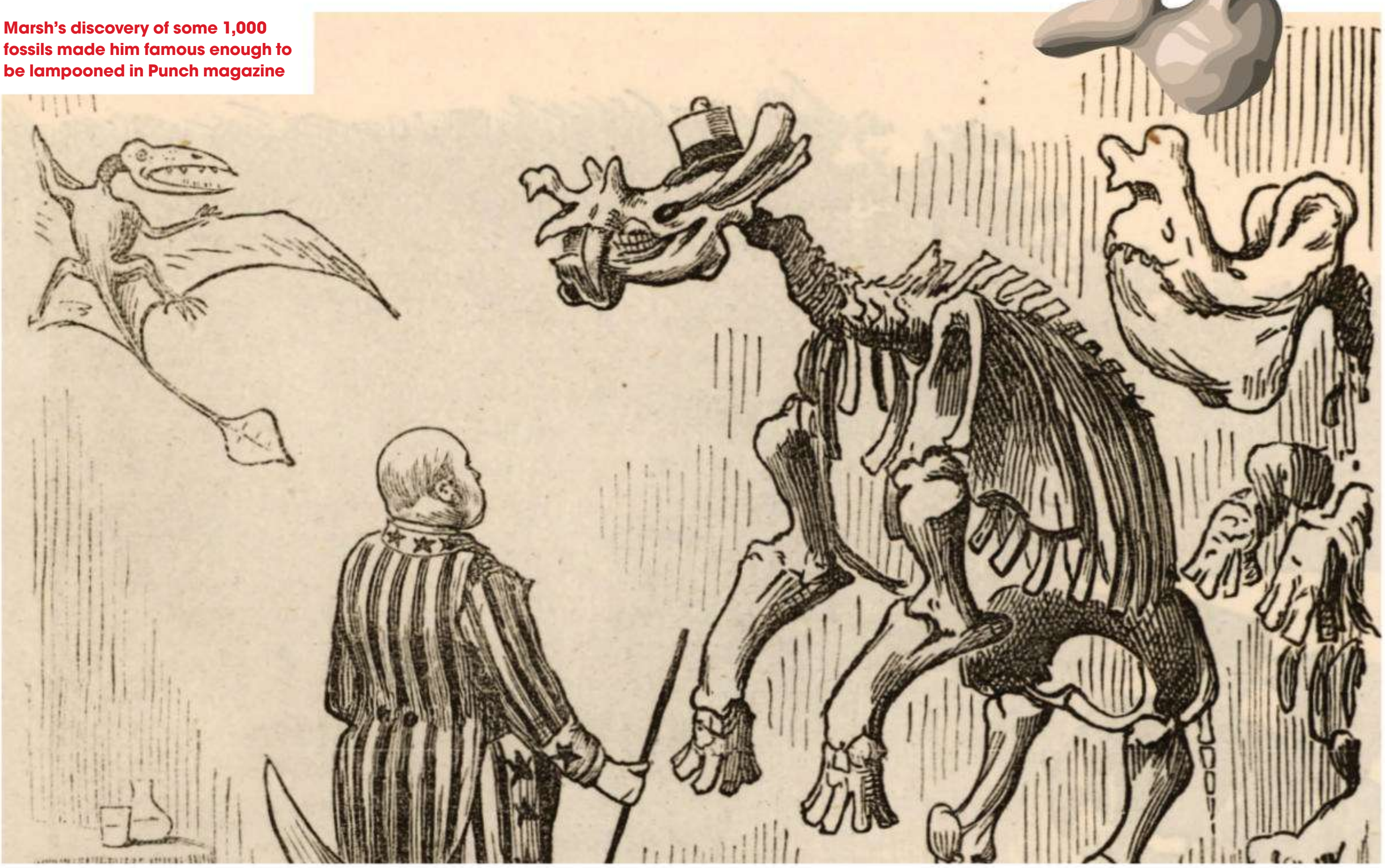
One of Marsh's most notable finds was the igantic Apatosaurus. Here, however, Marsh had placed the head of a Brachiosaurus on an Apatosaurus skeleton and named it Brontosaurus, a mistake Cope revelled in publicising

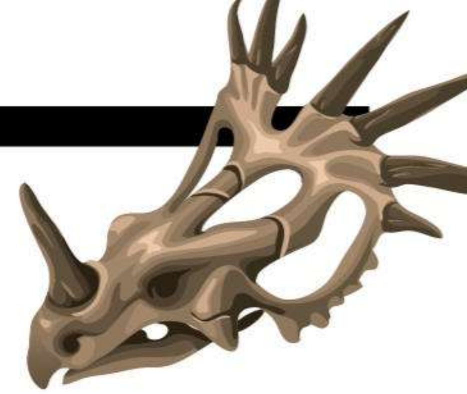


Too many toes

This specimen had splayed toes with too many claws, perhaps a result of the widespread belief dinosaurs were more related to modern-day reptiles than they've turned out to be

Marsh's discovery of some 1,000 fossils made him famous enough to be lampooned in Punch magazine





The not-quite-a-Brontosaurus

Marsh and Cope's race to publish led to a historic case of mistaken identity

Modern revision

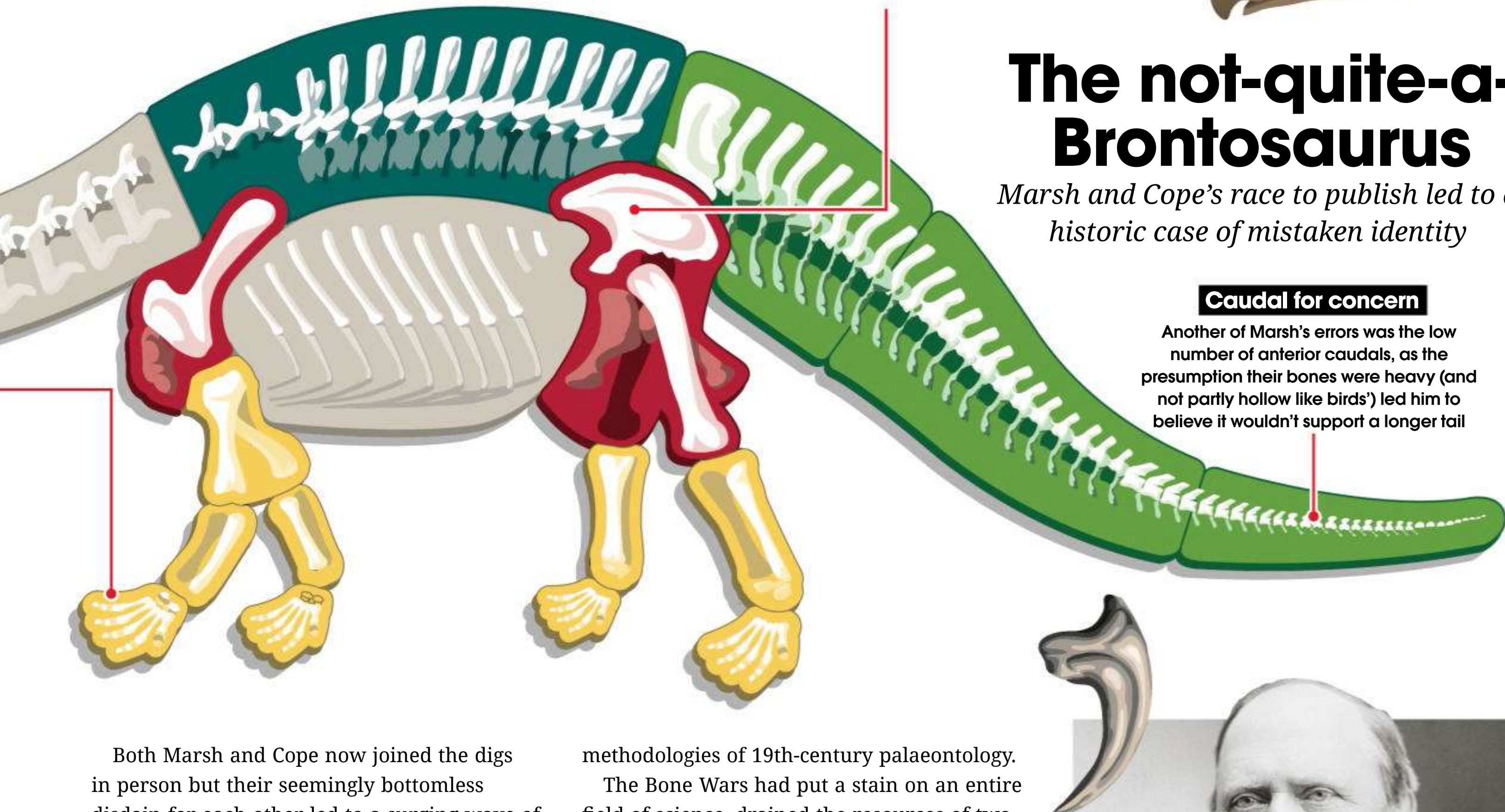
Although this Brontosaurus was debunked, the name resurfaced in 2015 to reclassify the Apatosaurus excelsus as Brontosaurus excelsus, due to it being substantially different enough to other Apatosauri to justify its own genus

Heavy hips

Another relic of the reptile connection ('dinosaur' is Greek for 'terrible lizard') is the size and placement of the hip bones resembling lizards rather than birds. Cope theorised that birds were descendants of dinosaurs — a theory that's been upheld

Caudal for concern

Another of Marsh's errors was the low number of anterior caudals, as the presumption their bones were heavy (and not partly hollow like birds') led him to believe it wouldn't support a longer tail



Both Marsh and Cope now joined the digs in person but their seemingly bottomless disdain for each other led to a surging wave of dissatisfaction among their respective teams. While Marsh's team soon suffered from mass resignations and in-fighting, Cope's was quickly running out of money to fund his resource-heavy expedition.

By the late 1880s, Cope was all but bankrupt, with Marsh not much better off himself. They had discovered over 130 new dinosaur species between them, with Marsh having named 80 dinosaurs, while Cope's tally stood at 56. Marsh had 'won' the Bone Wars, but at a great personal and professional cost to them both.

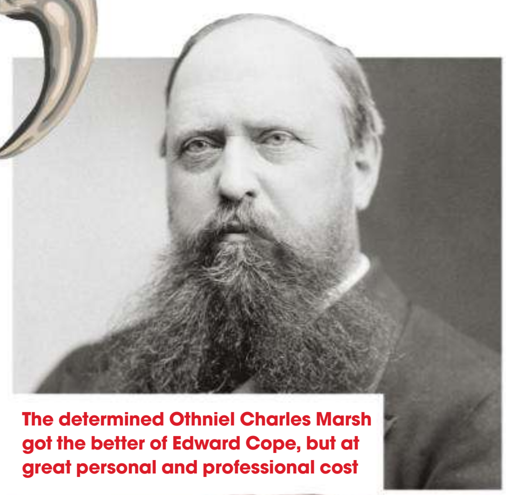
Forced to spend their later years relying on donations of fossils from third parties, they increasingly spent their discrediting each other via academic publications. In particular, Cope finally got his payback for the Elasmosaurus debacle. Cope discovered that Marsh had made a grave error in his assembly of a complete Apatosaurus, as its head turned out to belong to a Brontosaurus, an unrelated herbivore.

This was one of the final blows in their decades-long fight, and highlighted not only the depth of their rivalry, but also the rushed, error-prone and often unprofessional methodologies of 19th-century palaeontology.

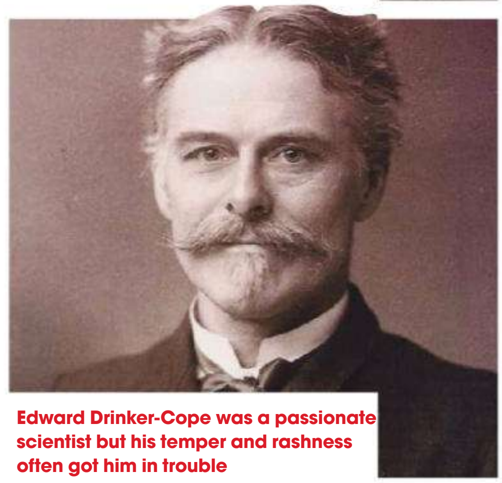
The Bone Wars had put a stain on an entire field of science, drained the resources of two of the century's greatest palaeontologists and ultimately drained their health, too. Cope ended up falling seriously ill in early 1897, by that time sleeping in a cot surrounded by piles of his fossils, and died in April aged just 56.

His final jab at Marsh came after his death. Having had his body donated to science in a letter issued at his death, he challenged Marsh to do the same so that their skulls could be compared to see which one of them had a bigger brain. Marsh died of pneumonia only two years later in March 1899 at the age of 67 – without ever responding to the challenge. He was interred in a graveyard in New Haven, Connecticut.

While many of their discoveries were less than accurate, they did lay important groundwork for today's field of palaeontology. And they certainly managed to ignite people's imagination and fascination with these ancient rulers of the Earth. The passion Cope, Marsh and many others put into their discoveries of dinosaurs in the 19th century, however fiery those turned, still inspires minds young and old today.



The determined Othniel Charles Marsh got the better of Edward Cope, but at great personal and professional cost



Edward Drinker-Cope was a passionate scientist but his temper and rashness often got him in trouble

Excavating is a slow process to avoid damaging the find

Though rarer, entire skeletons have been found perfectly preserved

Fossil hunting

In 2020, a fossil hunter discovered a completely new dinosaur species. Could you make the next big find?

How do you look for something that you aren't yet aware existed, from a world you can only try to imagine? It might seem impossible for us to study a species that we have never coexisted with, but this is something palaeontologists and fossil hunters do every day.

When humans first encountered dinosaurs, they had been extinct for over 65 million years. Everything we have come to know about dinosaurs today has been learned through our understanding of the planet's geology and analysing the ancient remains of these creatures. For this to happen, dinosaurs needed to have a lasting impact on the world, enduring tens of millions of years held inside solid rock. Luckily the remains of many types of dinosaur were preserved in the ground until humans could uncover them – and their secrets.

Fossils are impressions of ancient life, contained in the Earth's crust as a memento of life before the present. To palaeontologists they are hidden treasures, each with valuable information to share about a past geological and environmental age. The secret to their lasting form comes from the way they died. To become a fossil a dinosaur needed to take its last breath near water, or to have been buried alive.

Most dinosaurs wouldn't have died this way, so their remains would have deteriorated and can never be discovered. However, even for those that perished in one of these two ways, their bodies had to be surrounded by certain essential minerals to convert them into rock. Fossils are formed deep underground, where oxygen levels are so scarce that no bacteria can survive there. This means the body is unable to decay and lose its shape.

It's odd to think that these bones could be frozen in time only to be neatly retrieved from the ground as an almost-undisturbed stone skeleton. In some cases, not only are scientists presented with a perfect anatomical specimen to study, but they get an insight into a day in the life of a dinosaur – albeit their last day. Those that were suddenly buried alive can be retrieved in the exact position they died in. These are extremely rare fossils, but can provide information about the way a species lived.

Around the world, new dinosaur species are constantly emerging from rock faces, sandy dunes and clay-rich soils. But why are they being found now? To retrieve a fossil from sediment, the dinosaur first needs to be within reach. Sometimes it simply means being in the right place at the right time. You need to be near the land where the fossil has been held for millions of years just after the forces of nature have removed its rocky casing. The fossil then needs to be retrieved before the conditions above the ground erode or damage it and render it unrecognisable. The reason that the number of finds has increased in recent years is in large part due to our expanding knowledge of the dinosaurs and the evolving technology that helps us to study them.

More people are out looking for dinosaur fossils today than ever before. We now know where the best places to look are, what kind of shapes the eye should be drawn to and the best times of year to search. Knowing where to look and what to look for has increased the

Did you know?
The most fruitful locations for finding dinosaurs are North America, China and Argentina

© Getty / Shutterstock

success of beachcombing and geological digs.

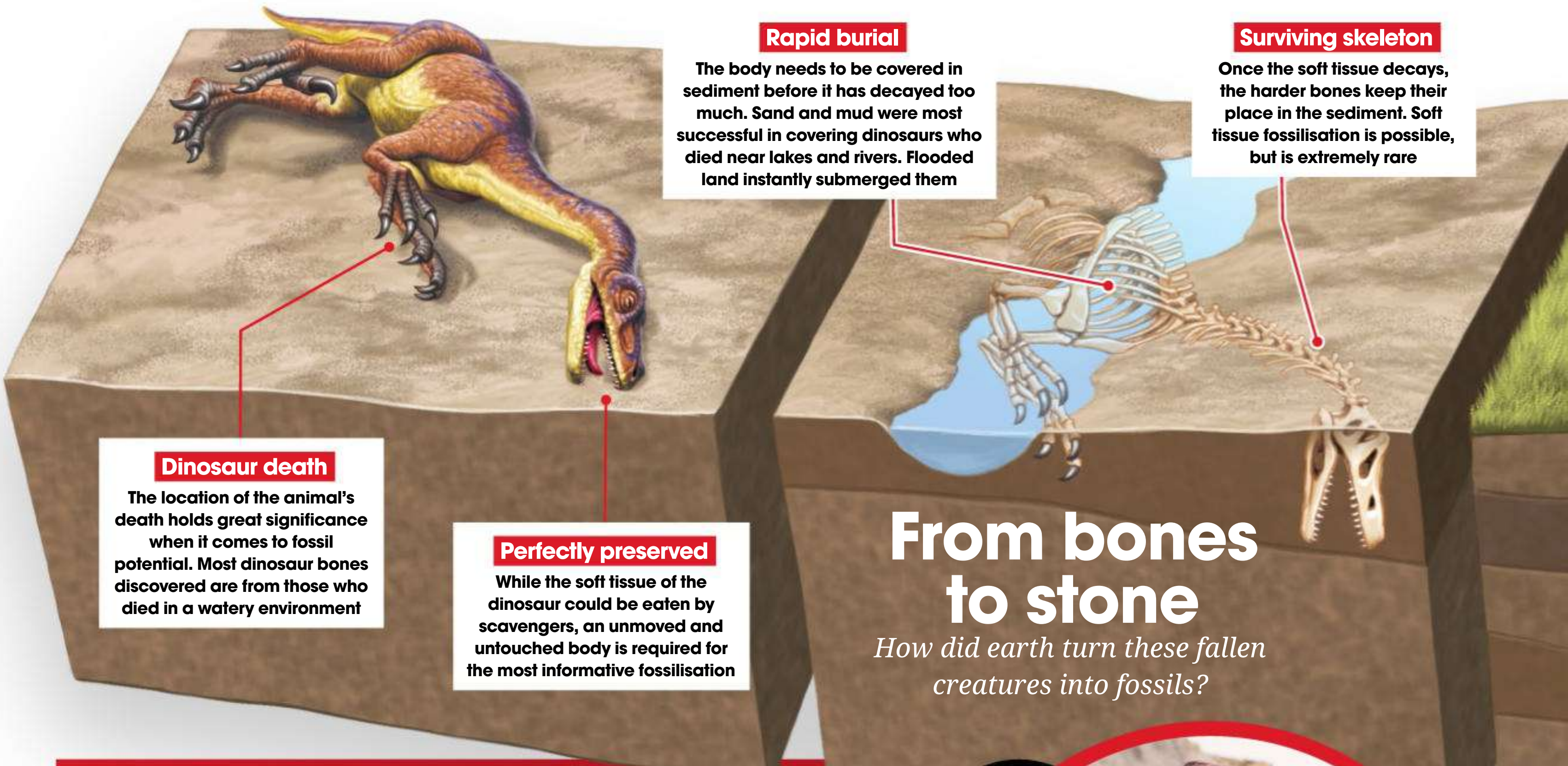
Although learning from previous finds enhances our understanding of what to look for next time, new species are often found in the least expected locations. One of the most recent dinosaur revelations was plucked from a British beach on the Isle of Wight in 2020, and after thorough research it was revealed to be a new species the following year.

This new species was retrieved from an unusual sediment type where the average fossil collector wouldn't think to search, showing that repeating methods of past finds doesn't always provide new results. This acts as an example that maybe the best way to search for something you don't know exists yet is not to search in conventional places at all. Sometimes the most notable fossils will find you.

The world of the dinosaurs seems so distant, but with every new species found we get closer to it. As our advancing knowledge of the relationship between each species grows, we have learned that dinosaur traits have been carried into the present day – and not just in their fossilised form. Modern birds actually originated in the Mesozoic Era, evolving from the theropod dinosaurs. Members of this group ranged drastically from the immense Tyrannosaurus rex to tiny bird-like creatures.

The sheer diversity between dinosaur species that have been discovered so far demonstrates just how much these animals evolved during their time on our planet. With every fossil that palaeontologists research, more pieces are added to the evolutionary story of the dinosaurs.

Perhaps one of the reasons humans have become so infatuated with these beasts that once ruled planet Earth is that we can relate to their domination. As a species that also appears to be thriving in great numbers, humans are discovering through ancient evidence that the forces of nature could overthrow us in an instant, turning us into a fossilised memory on par with the legendary dinosaurs that once roamed the ancient continents.



Rapid burial
The body needs to be covered in sediment before it has decayed too much. Sand and mud were most successful in covering dinosaurs who died near lakes and rivers. Flooded land instantly submerged them

Surviving skeleton
Once the soft tissue decays, the harder bones keep their place in the sediment. Soft tissue fossilisation is possible, but is extremely rare

Dinosaur death
The location of the animal's death holds great significance when it comes to fossil potential. Most dinosaur bones discovered are from those who died in a watery environment

Perfectly preserved
While the soft tissue of the dinosaur could be eaten by scavengers, an unmoved and untouched body is required for the most informative fossilisation

From bones to stone

How did earth turn these fallen creatures into fossils?

Find your own fossil

Anyone can find a fossil, but to increase your chances you need to know what you're looking for. Many beaches are embellished with ancient marine life forms, but to seek out dinosaur bones you'll need more luck and patience alongside your knowledge.

First, you need to understand the rocks. By finding out how old the rocks are in the area you're searching, you can tune your hunt to the kinds of species you are likely to find. Next, pick your time. You can find fossils all year round, but from November to April is usually best. This is because rough seas and winter winds create movement on the beach, and this time of increased erosion can expose new fossils from the cliffs.

Always ensure you keep safe while searching for fossils. There's no need to climb cliffs, as many can be found loose on the ground. For your first search at least, you should join an expedition organised by experienced fossil hunters. This can provide you with information on what to look for and further useful tips to carry with you on your next hunt.

You can learn how to break rocks without damaging any fossils inside

5 fossil types

Mold

The rock of a mold fossil details the outside of the organism. After the sediment around it hardens, the buried plant or animal is dissolved by water, leaving an empty mold for a fossil.

Source: © Pixabay/PublicDomainPictures

True form

These fossils are created when the body of an organism is replaced with rock. It displays the organism's true form in great detail, rather than just being an impression.

Source: © Pixabay/Adolfo Beato

Trace

Trace fossils aren't necessarily physical remains of an organism, but their formation displays traces of their existence. Examples include footprints, tooth marks and nests.

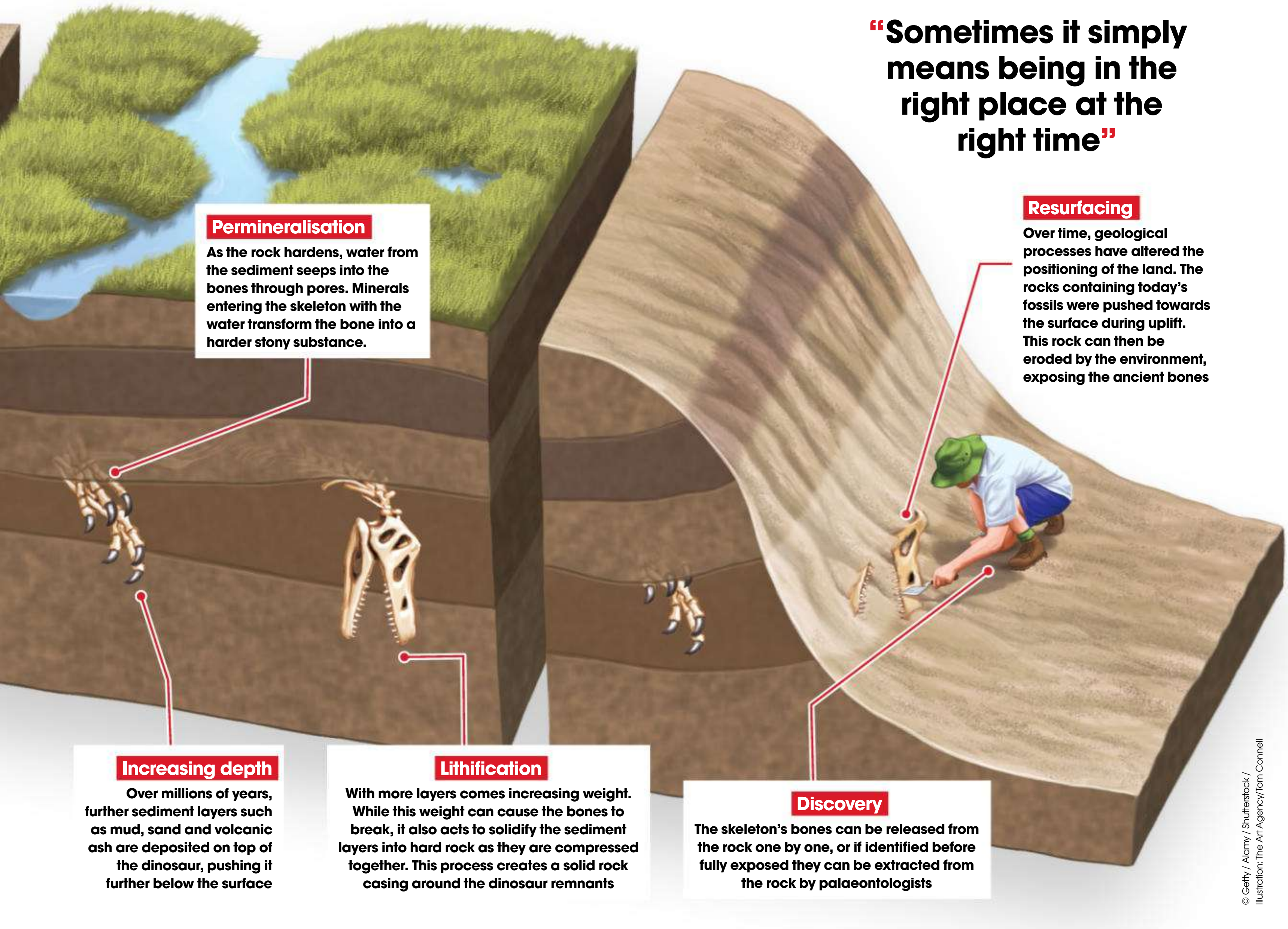
Carbonised

Created when a dead organism is buried on flat rock. Over time a thin carbon film is deposited onto the rock's surface. As the body decays, the carbon layer remains.

Cast

Cast fossils are more advanced mold fossils. Once the mold is created, the hollow area is filled with minerals, which harden to form a rocky version of the original organism.

"Sometimes it simply means being in the right place at the right time"



A new dinosaur

Discover how a new species was uncovered

It was revealed that four dinosaur bones found in 2020 on the Isle of Wight, England, are those of an entirely new dinosaur species. Since October 2019, these bones have been held at the University of Southampton, where palaeontologists have been hard at work trying to discover what animal they belong to. They soon realised, after comparing each minute detail to a computer database, that this species had never been seen before.

Named the Vectaerovenator inopinatus, it is a member of the theropod family of dinosaurs, making it a close relative of the Tyrannosaurus rex. Its given name sums up many of its discovered qualities.

'Inopinatus' means unexpected. What made these bones particularly interesting to palaeontologists is that they were found in the lower greensand. This is a marine sediment which is a rare location for dinosaur fossils and a likely reason why the species had not been located before.

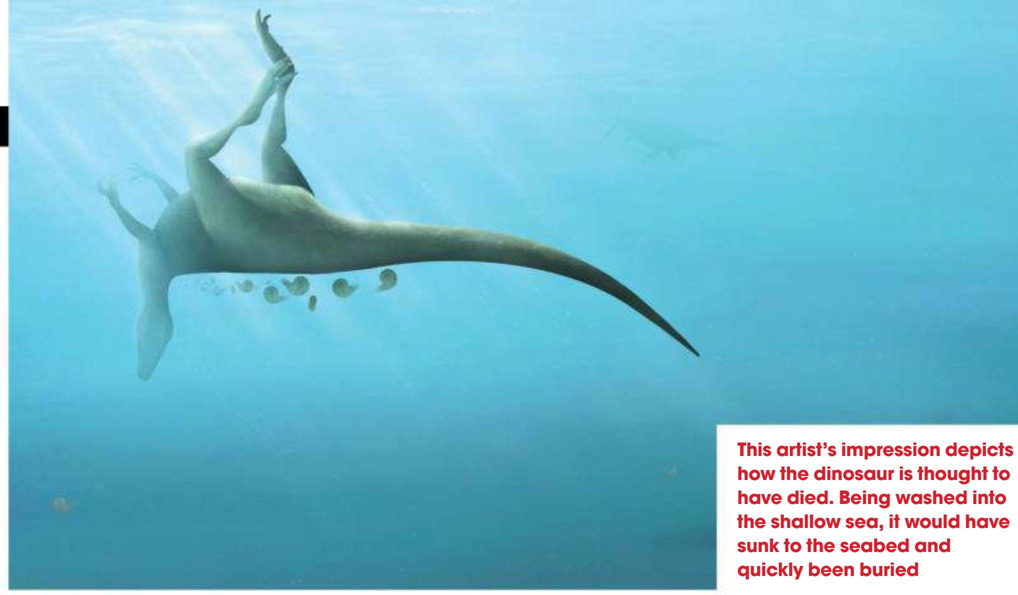
Neil Gostling, who supervised the study, said: "The Isle of Wight is the best place to find dinosaurs in Europe, but usually these finds are a terrestrial deposit. It is exciting because greensand is 116 million years old, and we have a poor understanding of European dinosaurs in this time period."

'Aero', which is incorporated into the new species' name, means air in Latin, and refers to the hollow properties of the four bones studied. They have large holes which would have been extensions of lung tissue for gas exchange.

"This is a very efficient way of getting oxygen into the body," Gostling said, "which some other theropods have as well. [The four fossils] don't feel like rock because they're almost hollow."

Despite only four bones being studied from this dinosaur, the university has already determined specific details about this ancient creature. Since the release of the findings another two bones from the same species have been handed in, and the researchers hope to soon reveal further information about it.

Did you know?
Around the world, a new species of dinosaur is discovered nearly every week



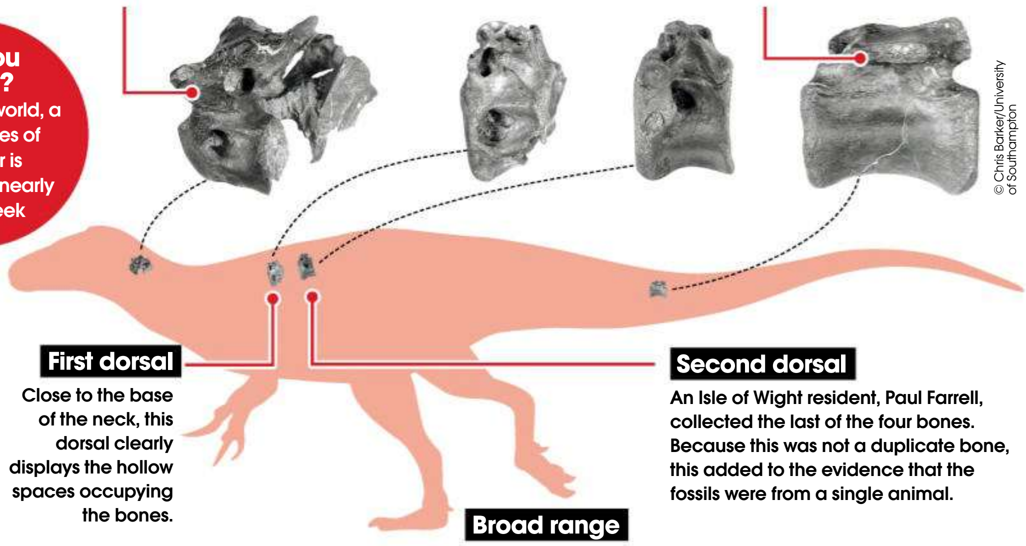
This artist's impression depicts how the dinosaur is thought to have died. Being washed into the shallow sea, it would have sunk to the seabed and quickly been buried

Placing the bones

How these fossilised finds fit together

Neck
This was the first bone to be found. When James Lockyer discovered this vertebrae bone it was broken, but through comparison to other similarly shaped theropod bones, this bone is thought to have been placed high in the dinosaur's neck.

Tail
This is a caudal bone, one of the two bones found by Ward. Theropods' tails were relatively long compared to their bodies, and were muscular to support the standing dinosaur.



First dorsal
Close to the base of the neck, this dorsal clearly displays the hollow spaces occupying the bones.

Second dorsal
An Isle of Wight resident, Paul Farrell, collected the last of the four bones. Because this was not a duplicate bone, this added to the evidence that the fossils were from a single animal.

Broad range
With the samples spanning across the length of the dinosaur's body from head to tail, the findings suggest the whole animal sunk into the ground as one complete body to be preserved.

How does the new theropod compare to other group members?

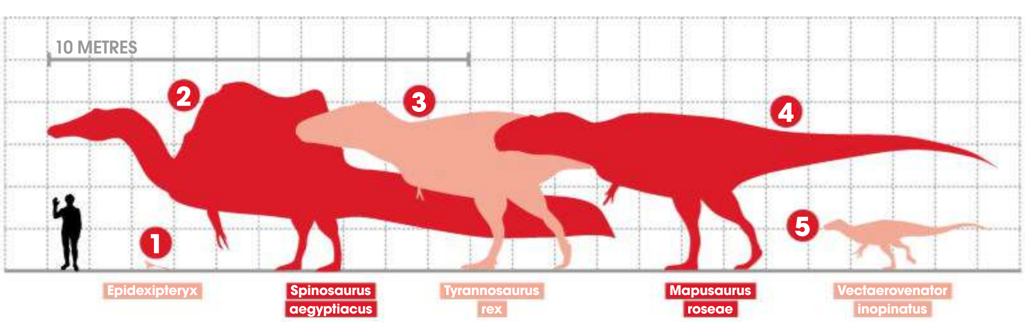
1 **160g** The smaller Epidexipteryx weighed the same as a billiard ball.

2 **7,500kg** Spinosaurus aegyptiacus was as heavy as 11 cows.

3 **12 metres** The Tyrannosaurus rex could be long as a school bus.

4 **1.8 metres** The head of a Mapusaurus roseae was the size of a bathtub.

5 **4 metres** Vectaerovenator inopinatus was about twice the length of a full-sized bed.



Ward discovered two of the dinosaur's bones

Lockyer found a bone from the neck

© Robin Ward / James Lockyer

Q&A

Fossil hunters who hit the jackpot

Robin Ward and James Lockyer weren't expecting to find a new dinosaur species when they visited the Isle of Wight. In March 2019, Lockyer discovered one of the dinosaur's bones, and Ward found two more in May. The fourth bone involved in the study of this species was collected by Paul Farrell.

What brought you to the Isle of Wight?

RW: I have been to the Isle of Wight a few times, but it was my daughter who chose to go there this time, as it was her tenth birthday. When we arrived we were too early to check into the hotel, so we decided to go fossil hunting on Shanklin Beach while we waited.

JL: I have been fossil hunting for the last 10 to 15 years and went to the Isle of Wight because it is an area with rapid erosion of the cliffs. Because of that, it's a good place to find fossils.

How did you come across the bones?

RW: As I searched the rocky area, I knew a find was possible because there had just been a high tide, which could uncover fossils from the sand. When I came across the first one on the floor, I videoed myself picking it up and posted it online. I knew it was from a dinosaur. I found the second just five minutes later, about eight feet [2.4 metres] away. I was so chuffed I did a bit of a jig on the beach. It's the find of a lifetime.

JL: I was told I wouldn't find much on Shanklin Beach, but I like to look in areas where others don't. I began searching the foreshore among the rocks and there it was – half a vertebrae – popping out the rocky substrate. I went to wash it in the sea and saw that it had a nice shape to it.

> **"I was told I wouldn't find much on Shanklin Beach"**

When were you made aware of the significance of your find?

RW: The first was clearly a dinosaur bone. The second one was a different shape, but looked like the same rock. They were so close I thought they had to be from the same dinosaur, and they were. Two days later I went to the Dinosaur Isle museum to see what I had found. The palaeontologists' eyes lit up as soon as they saw them. They couldn't find anything like them in their exhibit. It was only after they had been properly researched that I found out it was a new species.

JL: I knew I had found a vertebrae as I have an interest in archaeology and I am quite good at spotting bones. I also knew it was a fossil. At the museum, they were very interested in it but weren't sure what it was. They said it was the best find of the year so far. But it was when they got involved with the University of Southampton that things got more interesting and they established what it really was.

How does it feel to be linked to the discovery of this species?

RW: It's like winning the lottery. I fossil hunt all the time. Whenever I have five minutes I'll be looking through some gravel, but a dinosaur bone is the ultimate find. Gifting the bones to the museum was a bit like winning the lottery and then giving your money away, but if I hadn't they would only have had half of the bones they had to research, and I wouldn't know they were something special.

JL: It was nice to find it in the first place, but as time went on and I learned more about it, it got even more exciting. I think it's incredible that the university has the technology to identify something that we didn't even know existed. In a lifetime it is nice to have one notable find. To me all fossils are interesting to find, but to have my name against this find is exciting.

What do you like about fossil hunting?

RW: When you crack open a stone, most of the time there will be nothing in it, but when you do find something, you're the first person on Earth who's ever seen it. That's such a good feeling in itself.

JL: Ever since I was young I've liked searching. I was always digging holes in the garden. I didn't always know what I was collecting until I started fossil hunting more seriously and began learning about the geology of what I was finding. The best bit is not knowing what you're going to find. A lot of the time you don't find anything, so when you do there is a thrill.

How does this dinosaur compare to your previous finds?

RW: This was my best find in the fact that it is a new species. I have also got an ichthyosaur skull, which was a cool find. That was a reptile that swam in the sea a bit like a dolphin.
I've had many less successful searches. Once I found a shell which was probably 400 million years old. I threw it over to my son to have a look and he chucked it straight into the sea, thinking it was just a stone. No one will see that ever again.

JL: I've found marine reptile bones and various other fossil types. One of my personal favourites has been fossilised seeds. They are fascinating because they look like the seeds we have today but they are millions of years old. It's quite incredible to think that would have been the life of a new plant.

Five fantastic finds

Discovered fossils of some of the most mesmerising moments in prehistory

Did you know?
So far nearly 700 dinosaur species have been identified

2 Largest T rex Canada 1991

The Tyrannosaurus rex is probably the world's most well-known dinosaur. Their towering stature contrasts comically with their dinky arms. After more than 20 years, research of Scotty brought this enormous species to a new level. At 13 metres long, his leg bones suggest that he would have carried a weight of 8,870 kilograms. This makes him the largest of his kind to be found.

© Kumiko

4 Bird-like behaviour Mongolia 1994

This small theropod, Citipati osmolskae, was fossilised while protecting its eggs between 83 and 66 million years ago. Spread out across its nest, just as birds often do, this find confirmed that nesting is an ancient behaviour. Uncovered from the sand of the Gobi Desert, the positioning of the body over the nest made it clear to palaeontologists that this species was guarding its young. This was the first substantial evidence showing this behaviour.

© Dinoguy2/Wikimedia Commons

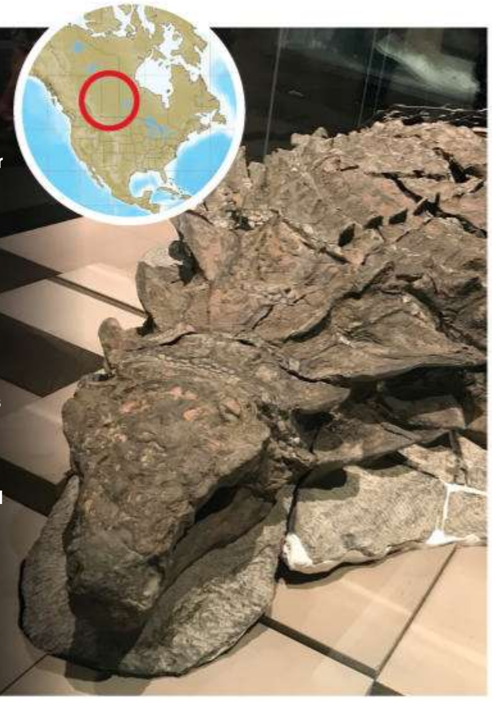
1 Forever fighting Mongolia 1971

When these dinosaurs began this fight around 80 million years ago, they probably didn't know they were fighting to the death... of them both. This fossil of a Velociraptor and a Protoceratops was discovered in a tangled scrap within the Gobi Desert's sandstone cliffs. The Velociraptor has its foot claw in the neck of the Proceratops, which is biting back at its opponent's arm. It is believed that a sudden sand flow buried them mid-fight, freezing the moment.

© Yuya Tamai

3 Most preserved dinosaur Canada 2011

When miner Shawn Funk began digging in the Suncor Millennium Mine in Alberta, Canada, he wasn't expecting to unearth a 112-million-year-old armoured dinosaur. While this was impressive enough, this nodosaur had been preserved to keep the exact shape it flaunted while it roamed Earth. Because of its rapid sea burial, the dinosaur was below ground before it had time to begin decaying. The rock solidified around each scale, imprinting a detailed design on the petrified remains. The fossil provides scientists with extraordinary detail of the animal's skin, scale patterns and overall shape.



© ケラトプスユウタ

5 Dino embryos China 2017

Finding dinosaur eggs is relatively rare, as many were soft-shelled and unlikely to become fossils. But in an even rarer case, palaeontologists in northwest China stumbled across over 200 dinosaur eggs. Within these eggs, 16 preserved embryos were found. The huge number of eggs are thought to be in the same area because the land was continuously flooded, but the dinosaurs used the same nesting site over a period of time.

Inside a palaeontologist's tool kit

What do you need to access hidden fossils?

1 Chisel

Dinosaur fossils are often found within rocks. Using a chisel and a hammer, rocks can be chipped away to reveal the inside.

2 Walkie-talkie

Some of the best finds are in extremely remote locations. If a group of fossil hunters splits up, contact with a designated base camp can be essential.

3 GPS

Keeping a record of where you are while looking for dinosaurs adds an element of safety. It is also ideal for documenting the exact location of the find.

4 Pointed-tip rock hammer

This tool is designed for use on hard rock. The flat end is used to crack open the rock and see inside without damaging any potential fossils within. The pointed end is used to dig a sample of the rock to analyse its mineral components.

5 Small probes and chisels

Accessing fossils can be a delicate procedure, requiring these small utensils. Fine-pointed picks work to uncover small fossils.

6 Dust brush

If fossils are covered in rock debris and dirt, soft brushes are a perfect way to reveal them without causing damage.

7 Swiss army knife

Compact and containing an assortment of small tools for every job, swiss army knives can be used to manipulate the rock on small samples.

8 Vinac

This solution of polyvinyl acetate adds a preservative coating to fossil finds. To stabilise dinosaur bones and stop them from breaking, they can be coated in vinac. The thin solution can be easily removed in a fossil laboratory later on.

9 Pens and bags

Fossils aren't always uncovered in one piece, with many found fragment by fragment. Plastic bags can hold pieces of a fossil together while you can use a pen to document how and where they were found, for future reference.

10 Measuring tape

Recording plenty of information about a fossil and its finding place is useful when it comes to researching the find. Measuring the distance between two found fossils can be useful in determining the likelihood that the bones are from the same animal.

Extinct behaviour

Fossils can provide incredible details about dinosaurs' anatomy and what they looked like, but what can they teach us about their lifestyles? These limited remains don't tell us everything, often leaving scientists guessing about the colour of their scales and the sound of their roars. But when it comes to their behaviour, palaeontologists can analyse data from the fossils' locations and shapes of their features to link them to possible behaviours.

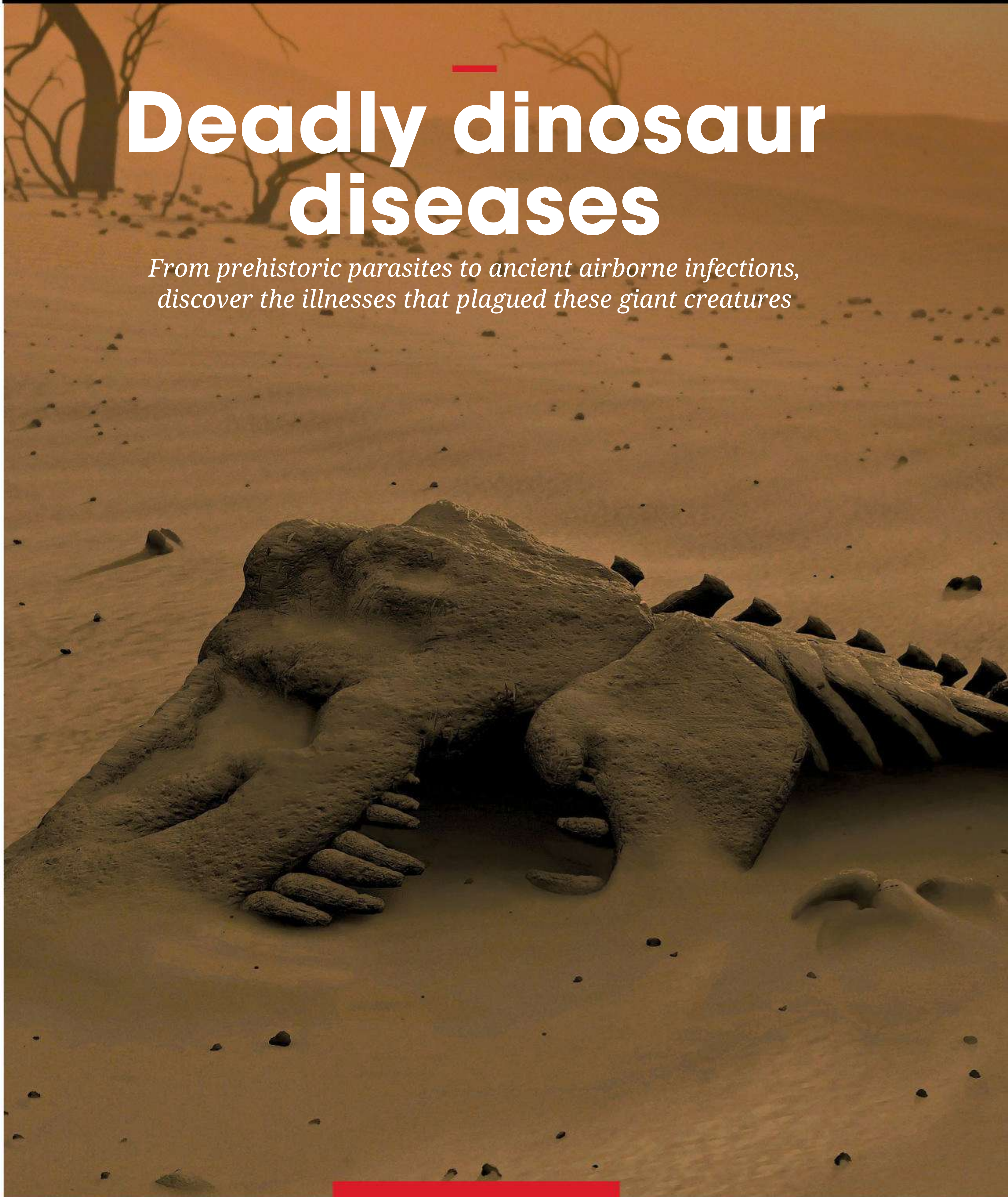
The size and shape of a dinosaur's teeth would have adapted to suit their diet, with long, sharp teeth indicating an animal that feasted on the meat of other animals. In some of the rarest fossils the contents of the stomach have been preserved – an even clearer answer to what was eaten.

When there is a combination of features all suiting a particular behaviour, this cements the hypothesis further towards certainty. Scientists can find clues in the structure of claws, fingers, wrists, joints and backbones that benefit a dinosaur's ability to dig. When all of these features are present, this abundance of data paints a likely picture.

Dinosaurs with short thighs and long feet are believed to have been quick runners over long distances

Deadly dinosaur diseases

From prehistoric parasites to ancient airborne infections, discover the illnesses that plagued these giant creatures



We all know the Tyrannosaurus rex terrorised Triceratops on land. Many of us can picture Pterosaurs diving down from the skies to snatch smaller prey. A few might even know the Mosasaurus, the leviathan that ruled the ancient oceans. But while these mighty carnivores loom large in how we imagine the age of dinosaurs, there was a far greater threat that we forget – an invisible foe that would strike without warning and killed millions more creatures in the Mesozoic era than any other: illness.

It's no surprise that dinosaurs got sick. They were living, breathing creatures just like us. But we know very little about what actual diseases made these ancient creatures ill. This is because you can identify signs of injuries like broken limbs and battle scars in the fossil record – often with little more than a magnifying glass – but diagnosing illness is far more difficult. It's not just that bacteria and viruses are microscopic. Diseases mostly attack internal organs, which are made of fleshy soft tissue and usually rot too quickly to be preserved.

On rare occasions, some dinosaur flesh remains. The remnants of a ravenous raptor's guts were discovered in China in 2022 and the brain tissue of an Iguanodon-like herbivore in the UK in 2016. These were likely preserved only because the dinosaurs' bodies were submerged in bog-like water. But more often than not, paleopathologists – researchers of ancient diseases – have to make do by assessing fossilised bones for rare signs of severe illness.

Did you know?
You can explore hundreds of CT scans of dinosaur bones from the University of Texas at digimorph.org

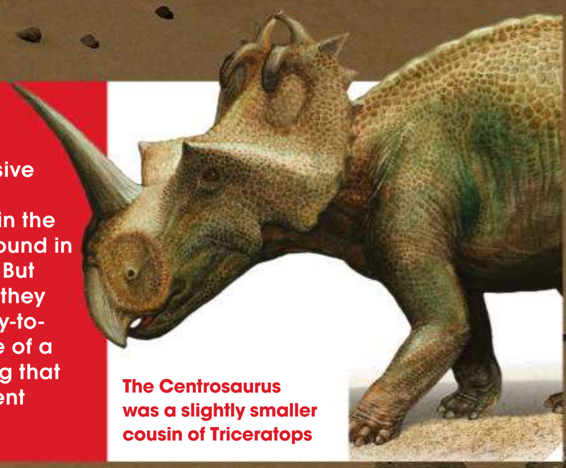
However, modern technology is helping these researchers delve deeper for clues. 20 years after it was invented for use in medical diagnosis, computed tomography scans, or CT scans as they're better known, are being used to see inside fossils. This process uses X-rays, but the results are much more detailed than the X-ray you might get at the hospital if you broke your leg. They are high-resolution 3D reconstructions that you can zoom in and out of to fully explore the structures. This can reveal lesions and deformities buried in bones that are telltale signs of infections but would be unidentifiable from the outside.


Palaeontologists scan fossils with higher X-ray doses than you could use on a living patient

Dinosaurs battled cancer too

New research suggests dinosaurs could suffer from cancer. The evidence was dug up in 1989, but it just wasn't recognised until recently. A Centrosaurus apertus was uncovered in Alberta, Canada, with a misshapen shin bone. Experts at the time thought it was a poorly healed injury. But another team of scientists – bringing together pathologists, a surgeon and a radiologist as well as palaeontologists – reexamined the fossil in 2020 using high-resolution X-ray CT scans. They diagnosed the deformity as osteosarcoma, an aggressive bone cancer also found in humans.

This isn't the only example of cancer in the fossil record. Tumours have also been found in T rex and duck-billed Bonapartesaurus. But both appeared to be benign, meaning they didn't seriously affect the dinosaur's day-to-day life. Instead, this is the first example of a malignant tumour in dinosaurs, meaning that the cancer could have spread to different parts of the body and become deadly.


The Centrosaurus was a slightly smaller cousin of Triceratops

As palaeontologists expand the techniques they use to analyse fossils, they're also drafting different kinds of experts to help them. Doctors and radiologists have helped by comparing CT scans of fossils with human medical records to look for similarities, while veterinary scientists have shared their knowledge of how diseases manifest in other reptiles like crocodiles, as well as birds, which evolved directly from dinosaurs. This new approach is overturning previous research. Fossils that were thought to be twisted bones or bite marks proved to be far more interesting. By diagnosing these primordial illnesses, we learn more about the dinosaurs they afflicted. We better understand their biology as we discover illnesses they share with modern-day animals. The types of diseases and how they may have spread also hint at how dinosaurs behaved with members of the same species, as well as the relationship between predators and prey.

While Dolly's exact species is unknown, they were related to Diplodocus and Brontosaurus

A very sauro-throat

Imagine how bad a tickly throat must feel if your neck is 25 metres long. There wouldn't be enough chamomile tea in the world to soothe it! A sauropod nicknamed Dolly had a serious case of the sniffles. This included a cough, trouble breathing and a fever, according to scientists. The infection was so severe that it marked the creature's neck vertebrae, which we can still see in the fossil today. While Dolly is the first confirmed case of a dinosaur with an airborne illness, possible signs of tuberculosis were found on the rib of a Titanosaur, another sauropod, in 2021.

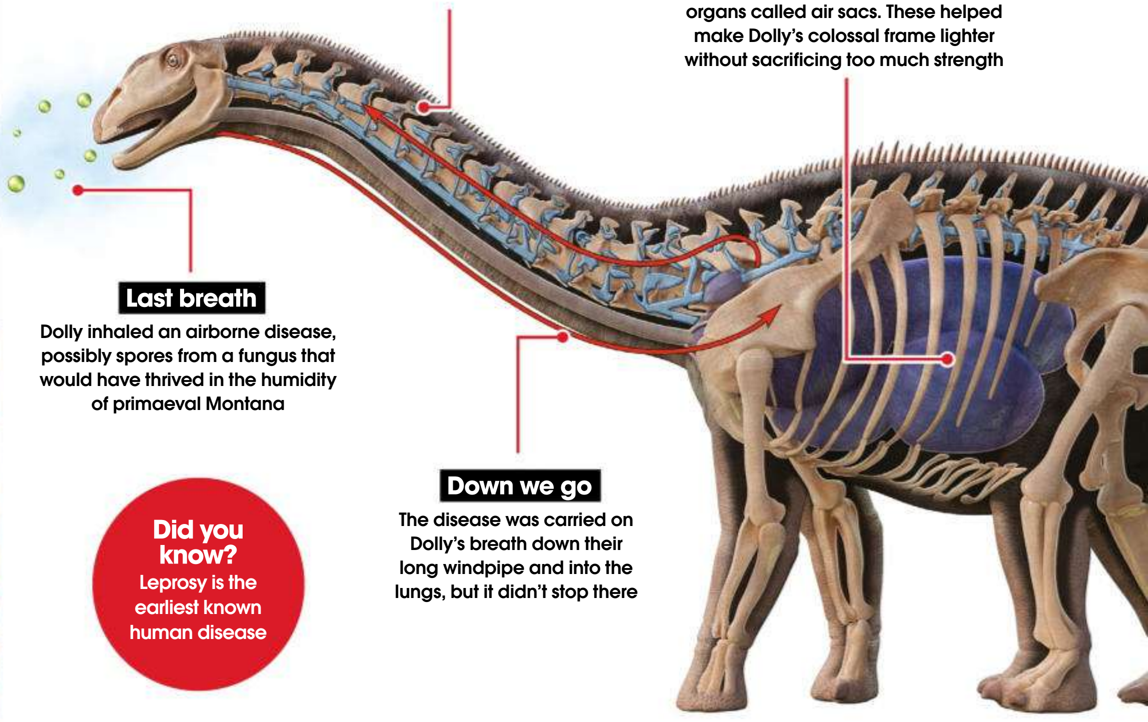
Duckbill bone disease

Some 70 million years ago, a Hadrosaur lived alongside a shallow sea covering what is now New Jersey. It had a real pain in the arm, which two centuries after it was unearthed we know was due to septic arthritis – the first known case in a dinosaur. This is a common bone disease that often develops when an injury becomes infected. A CT scan revealed signs of erosion within two arm bones, with a porous texture instead of healthy, dense bone tissue. On the outside, both bones had bulges, and spurs of new bone had formed. In fact, when excavated the pioneering 19th-century palaeontologist reported that the two bones were fused, but the brittle fossil had broken apart.

The Hadrosaur was a rare find on the US' East Coast, which has few fossils

Ancient autopsy: Dolly the dinosaur

This respiratory infection would've been a real pain in the neck – and the air sac



No signs of recovery

The disease lodged in an air sac within Dolly's thorax. Unfortunately, the infection was likely chronic and possibly fatal

Breathing space

Like birds today, air circulated through hollow bones and inflatable organs called air sacs. These helped make Dolly's colossal frame lighter without sacrificing too much strength

Last breath

Dolly inhaled an airborne disease, possibly spores from a fungus that would have thrived in the humidity of primaeval Montana

Down we go

The disease was carried on Dolly's breath down their long windpipe and into the lungs, but it didn't stop there

Did you know?

Leprosy is the earliest known human disease

T rex's terminal toothache

The T rex was the king of the Late Cretaceous period. It boasted a mouthful of banana-sized teeth and a biting force of 3,500 kilograms – that's like the impact of three small cars. But these champion chompers were also the apex predator's weak spot. "Some of the world's most famous T rex specimens have these holes in their jaws," says Dr Steve Salisbury from the University of Queensland. "Some specimens look like Swiss cheese." Working with a small team, Salisbury examined over 60 T rex fossils. This included Sue, one of the best preserved skeletons, which is on display at Chicago's Field Museum.

"We now believe that these holes are caused by an infectious disease called trichomonosis," Salisbury says. This is an illness caused by microscopic parasites. Many pigeons carry it today but are immune. But hawks and falcons that eat pigeons can get very sick, developing lesions in their lower beaks. It's possible that T rex caught the infection from their prey too. But the fierce theropods were also known to fight among themselves. "We don't think it's a coincidence that a significant number of adult tyrannosaur specimens show both face-biting marks and evidence of a trichomoniasis-like disease," Salisbury says. "Fighting, and specifically head-biting, would have been an ideal mechanism for spreading the disease among tyrannosaurs." However it was caught, the infection would have meant a slow, painful death. It would have made it harder and harder for the creature to eat until it starved.

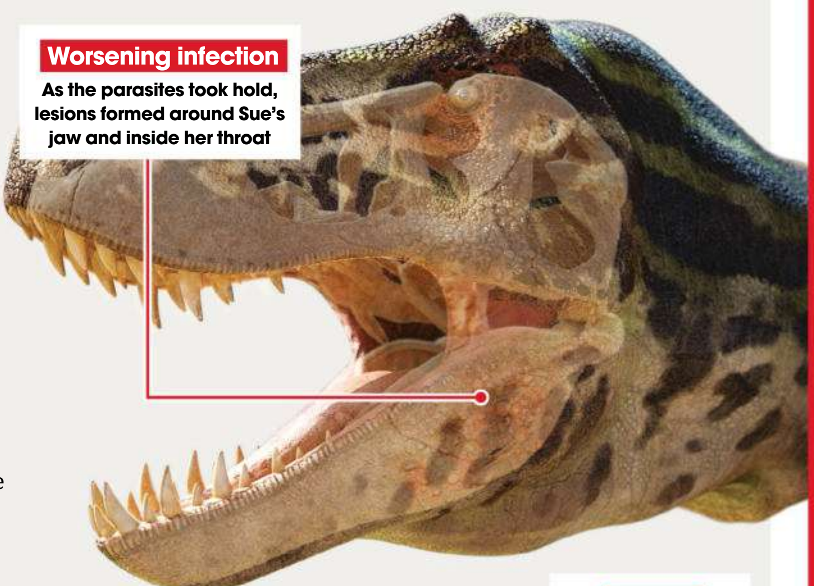
A close examination suggests Sue was 28 years old when she died – very old for a T rex

Ancient autopsy: Sue the T rex

No trip to the dentist would have saved Sue

Parasitic invasion

Sue was infected with tiny single-celled parasites that buried into her giant jaws and fed on the tissue



Worsening infection

As the parasites took hold, lesions formed around Sue's jaw and inside her throat

Lasting damage

The parasites cut through the skin and ate into the jawbone, making deep holes we can see in fossils today

5 Different dino deaths

Getting eaten

1 It was a dino-eat-dino world. We know of at least 100 meat-eating dinosaurs, ranging from the crow-sized Microraptor to the enormous Spinosaurus, which at 14 metres long was three times the size of an African elephant.

Getting bitten

2 You might consider yourself lucky to escape a hungry carnivore. But even a scratch could be deadly if it became infected with germs. A towering sauropod in China was discovered with signs of a pus-marked injury caused by either tooth or claw.

Breaking bones

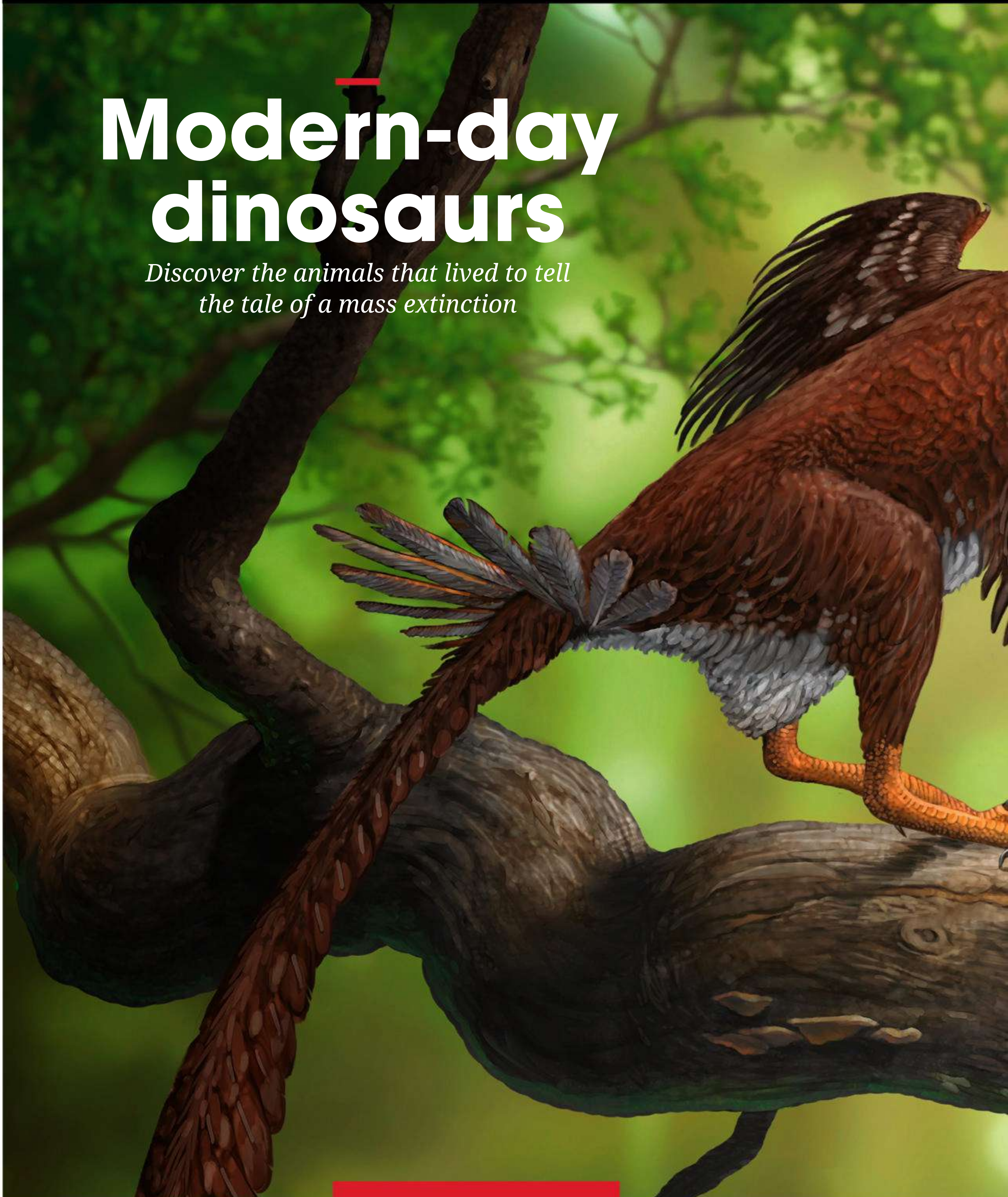
3 Broken bones litter the fossil record. While many show signs of healing, meaning the creatures survived, others show signs of becoming terminally infected. But not all of these injuries were from combat. Evidence suggests theropods like the T rex were prone to falling over.

Natural disaster

4 Geology suggests that volcanic eruptions were commonplace 65 to 70 million years ago, which would have been explosive and devastating. While a herd of thousands of Centrosaurus were struck down in a flood 77 million years ago, possibly caused by a tropical storm.

Asteroid annihilation

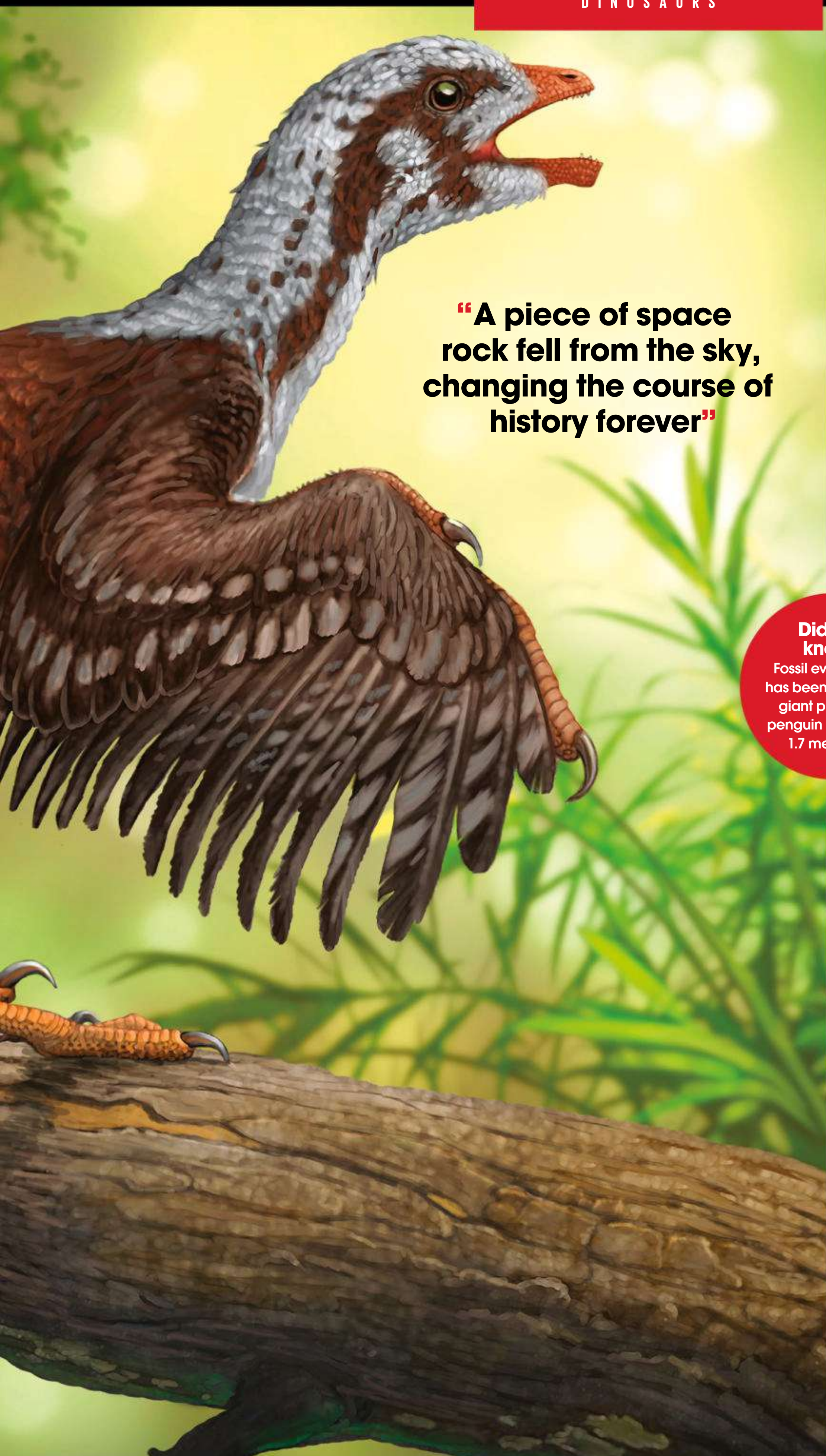
5 It only took one asteroid strike 66 million years ago to wipe out the dinosaurs. The impact caused catastrophic wildfires, earthquakes, tsunamis and a dust cloud that blocked sunlight for a year.



Modern-day dinosaurs

Discover the animals that lived to tell the tale of a mass extinction

EXTINCTION & LEGACY



"A piece of space rock fell from the sky, changing the course of history forever"

With lush green jungles and the sweet scent of the first flowering plants filling the air, the Cretaceous period saw the planet at its prehistoric prime. Giants dominated the land, sea and skies up until around 66 million years ago, thriving in the abundance of life occupying Earth. That was of course until a huge piece of space rock fell from the sky, obliterating the dinosaurs and changing the course of history forever. But, some species managed to cling on to life and avoid extinction.

Defining the dinosaurs

Dinosaurs are a group of reptiles that evolved from a class of creatures called archosaurs ('ruling reptiles'). The archosaurs evolved around 250 million years ago, eventually dividing into two different lineages: one evolutionary branch gave rise to the ancestors of crocodiles (Pseudosuchia) while the other led to the evolution of pterosaurs, dinosaurs, and eventually birds (Ornithosuchia). All these creatures – even the birds and crocodiles alive today – share a common archosaur ancestor.

Did you know?
Fossil evidence of has been found of a giant prehistoric penguin measuring 1.7 metres tall

One of the first dinosaurs to take its steps some 230 million years ago during the Triassic period was a small, speedy, two-legged omnivorous dinosaur called the eoraptor. 15 million years later, any animal on Earth with a length of one metre or more was a dinosaur. These beasts evolved to fill lots of different ecological niches, from towering titanosaurs to miniature microraptors. Dinosaurs were widespread on our planet, dominating the land for over 160 million years before a cataclysmic event wiped out 75 per cent of all life on Earth.

The end of an era

The exact explanation for the demise of the dinosaurs had been debated for many years until a huge crater was discovered in Chicxulub, Mexico, in 1991, a finding that finally shed some light on the truth behind the violent end of these ancient titans.

Now known as the Cretaceous-Paleogene (K-Pg) extinction event, the dinosaurs were wiped out following the impact of a ten-kilometre-wide asteroid colliding with Earth at over 64,000 kilometres per hour. The explosive power of the impact gauged a 180-kilometre-wide hole in the Earth's surface and killed 80 per cent of the plants and animals living within its vicinity. Yet despite the incredible power of this event, the impact itself was not the sole cause of the global extinction: the atmospheric aftermath also played a key part.

Due to its sheer scale and size, the asteroid vaporised on impact, raining red-hot ash and creating a vast cloud of particulate pollution. Evolutionary biologist and broadcaster Dr Ben Garrod describes the devastation. "The area of impact was full of gypsum, and when gypsum is vaporised it makes this horrific acidic concoction that then falls as acid rain. This huge cloud of toxic gas, along with molten ash, was thrown into the atmosphere, creating a pizza oven effect, resulting in the Earth baking for months."

This fiery rain increased the Earth's global temperature to levels fatal to large reptiles with nowhere to go. However, it was the darkening of the sky that lead to the ultimate destruction of the dinosaurs. Acting like a curtain across Earth, this atmospheric debris shrouded the surface from sunlight. By removing light, plants could no longer photosynthesise properly. Since plants are an integral part of every food chain, without them a chain reaction of starvation swiftly followed. It was only those that could rely on alternative food sources that would live to witness the dawn of a new era.

Did you know?
There are an estimated 18,000 bird species currently living on Earth

Survival of the fittest

It may have caused the death of the dinosaurs on a global scale, but not all species were wiped out in this devastating mass extinction.

Crocodiles and alligators gradually shrank in order to survive the mass extinction

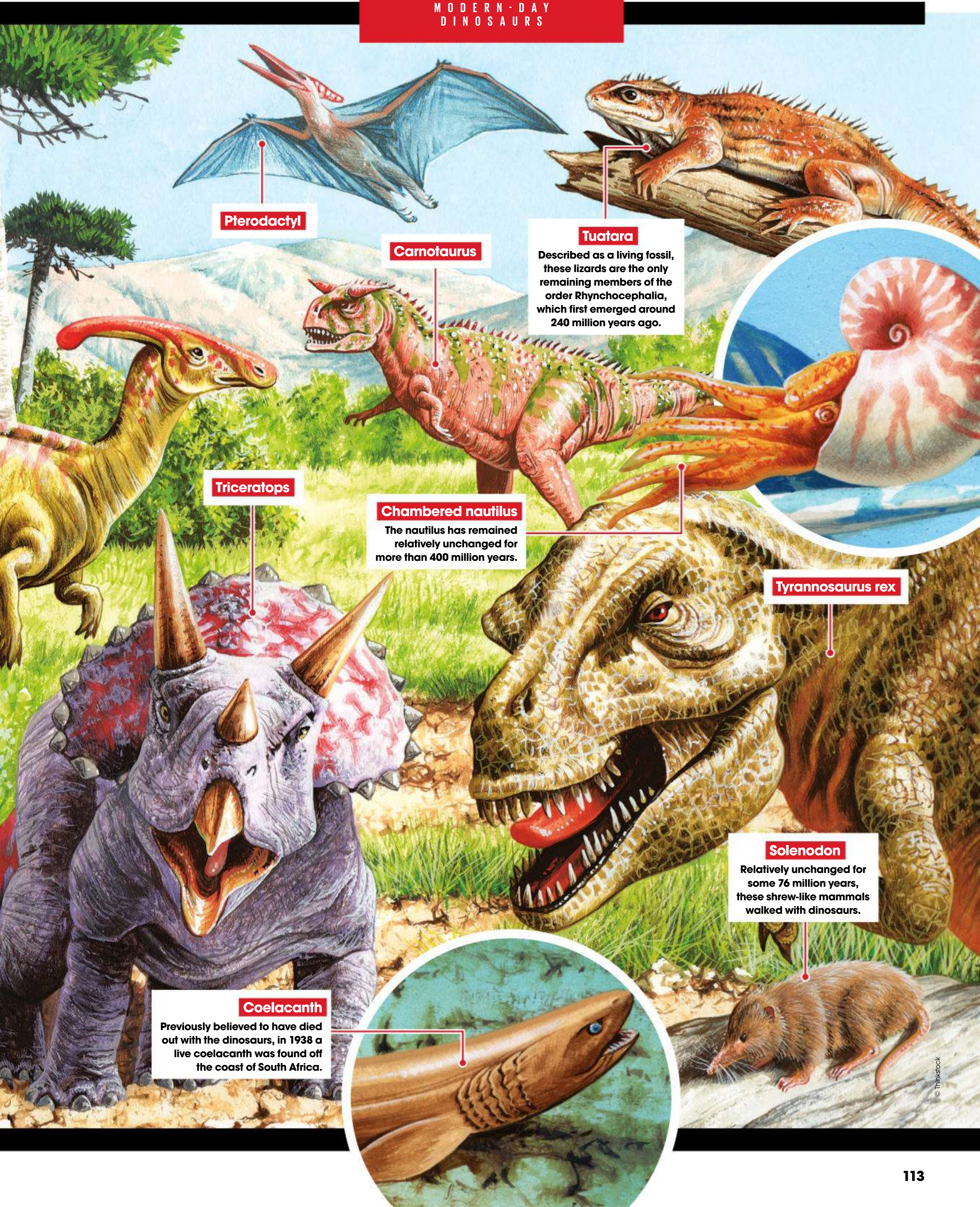
Dinosaur neighbours

Meet the modern creatures that descend from those that walked with dinosaurs

Snakes
Surviving the mass extinction, fossil evidence of snakes has been dated back 150 million years.

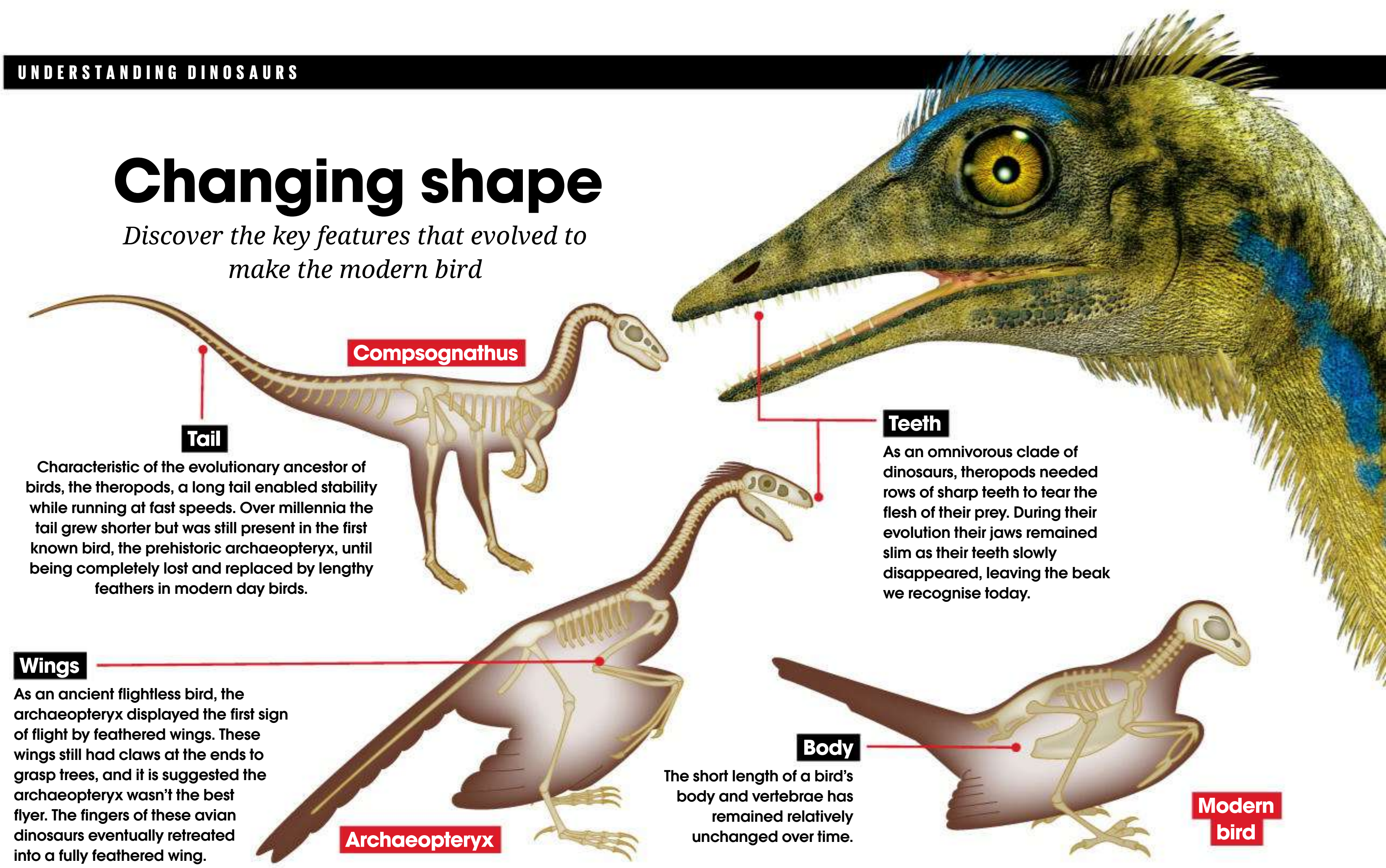
Parasaurolophus

Bees
Experiencing a mass extinction of their own, bees managed to claw their way back from decline.


Pterodactyl
Tuatara
Described as a living fossil, these lizards are the only remaining members of the order Rhynchocephalia, which first emerged around 240 million years ago.
Carnotaurus
Triceratops
Chambered nautilus
The nautilus has remained relatively unchanged for more than 400 million years.
Tyrannosaurus rex
Solenodon
Relatively unchanged for some 76 million years, these shrew-like mammals walked with dinosaurs.
Coelacanth
Previously believed to have died out with the dinosaurs, in 1938 a live coelacanth was found off the coast of South Africa.
© Thinkstock

Changing shape

Discover the key features that evolved to make the modern bird



To escape the intense heat of the falling ash and the cold global winter that followed, many of those that could dig or dive lived to see another day. In fact, it was the death of the dinosaurs that gave rise to the age of mammals.

Having sheltered from the impact below ground, the first true mammals soon emerged; creatures that could sustain themselves on invertebrates and plants. Arguably the most peculiar mammal members that survived the mass extinction were the egg-laying mammals: the platypus and echidna.

Those that took to the depths of the oceans also fared well, feasting on those relatively unaffected by the climatic change occurring above the waves. Sharks, for example, had hunted the oceans long before dinosaurs had taken their first steps and have lasted long after their departure. But there is one common feature that links all those that survived the catastrophe: their size.

"Size is definitely a big factor, anything bigger than the ten to 20 kilogram mark was gone. At the moment there is no evidence for anything even cow-size that survived. Most dinosaurs were relatively on the larger side. [On land] a lot of other reptiles, birds at the time, even quite a few mammals survived, but nothing other than that," explains Dr Garrod.

The ability to survive above and below the water enabled prehistoric crocodiles and alligators to gain the upper hand. Thick scales, a long jaw housing razor-sharp teeth and a substantial tail proved a useful arsenal in the quest for survival.

"Crocodiles are perfectly adapted to their environment; they can deal with really hostile situations, such as environments lacking

Did you know?
It's not just animals that lived alongside dinosaurs – monkey puzzle trees have existed for 200 million years

Theropods, meaning 'beast-footed', were the only large land carnivores for 100 million years in oxygen. The order Crocodilia evolved separately to dinosaurs. They are true reptiles and evolved 86-85 million years ago. So they were quite new on the scene," explains Dr Garrod.

As exotherms, crocodiles have been to seen to enter a stasis-like state to ensure their survival; a beneficial quality when dealing with a global climatic change, a quality the dinosaurs unfortunately did not possess. Size, as it did for any of the other species that survived the asteroid impact, played a massive role in the longevity of the crocodiles. Dwarf crocodiles living today are about the same size as their ancestors that escaped the brink of extinction.

Charles Darwin once wrote, "It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is most adaptable to change." With the planet labouring under such harsh conditions, only those able to adapt to their new environment survived and evolved into the species we see today. There is one group of animals in particular that not only survived the mass extinction but thrived after it.

Birds are the only living descendants of the dinosaurs

Feathered family

As direct descendants of dinosaurs still roaming the planet, birds have lost tooth and nail to maintain their stronghold on Earth. The first signs of a feathered future for dinosaurs began around 245 million years ago in the form of a group of dinosaurs called the theropods. This collection of reptiles balanced themselves on two hind legs with the help of a long tail, while two short forearms enabled them to grasp and pull apart the flesh of their prey. The foot of a theropod is the first visible similarity to a current-day bird, with three extended clawed toes protruding in front of a smaller back toe. Feathers soon followed in non-avian theropods such as the oviraptorosaur, but these dinosaurs still had not harnessed the power of flight.

Over millennia these dinosaurs steadily evolved into the first known winged dinosaur, the archaeopteryx, taking to the skies around 150 million years ago. During the next 80 or so million years, this clade of dinosaurs became smaller and smaller, losing the claws at the tips of their wings and replacing their teeth-laden jaws with beaks, and it was this transformation that was key to surviving the mass extinction.

Prehistoric birds similar in appearance to the ones we know today began to develop, such as the crow-like confuciusornis. Beaks and wings were the real saving grace for birds following the extinction event. As plant resources were declining, a lack of teeth enabled them to access seed and invertebrate food resources in a world where food was scarce. Their ability to fly gave them a distinct advantage over less fortunate land-dwelling animals, enabling them to reach areas of refuge.

The K-Pg extinction is one of five mass extinctions to date

"Birds have lost tooth and nail to maintain their stronghold on Earth"

"There must have been pockets of little oases around the world. Havens where nothing was touched, such as gorges or valleys. We don't know where they are yet, but there could be two or three little places potentially, or maybe dozens of places that were untouched, beautiful, lush, tropical places," explains Dr Garrod.

Without the now-deceased carnivorous giants hunting them, or their herbivorous counterparts consuming their weight in vegetation, birds and other small animals were able to sustain themselves, thus birthing the lineage of the living fossils we see today.

Wing evolution

*Based on the fossils found through the ages, palaeontologists have pieced together some important anatomical details that can help us reveal how wings developed from limbs**

***The illustrations below are examples of different stages of wing development, but don't represent a direct progression**

Sinosauropteryx **Unenlagia** **Archaeopteryx** **Eoalulavis** **Modern birds**

Resurrecting dinosaurs

Does the discovery of their cells – and possibly even DNA – mean we stand a chance of bringing these long-lost beasts back to life?

Staring at the screen in the darkened theatre of the visitor centre, Dr Ellie Sattler shakes her head and whispers, “Palaeo-DNA, from what source? Where do you get 100-million-year-old dinosaur blood?” We all know the scene. It’s ‘the science bit’ in *Jurassic Park* – the part apparently so convincing that it’s led science-fiction fans the world over to wonder why we can’t just patch together a dinosaur via the miracle of cloning. And wonder we might because, as it turns out, 100-million-year-old dinosaur blood may not be impossible to come by.

Since before *Jurassic Park*, Mary Schweitzer, a palaeontologist at North Carolina State University, has been finding traces of blood in the fossilised bones of dinosaurs. Textbooks tell us that blood and bone cells decay too readily to be found in the fossil record. But in 2005 in the journal Science, Schweitzer published pictures showing what looked like blood vessels and bone cells in the leg bone of a Tyrannosaurus rex. “We had all this soft tissue that was consistent with blood and bone cells in every way,” says Schweitzer. “I knew it completely went against what I had been taught.”

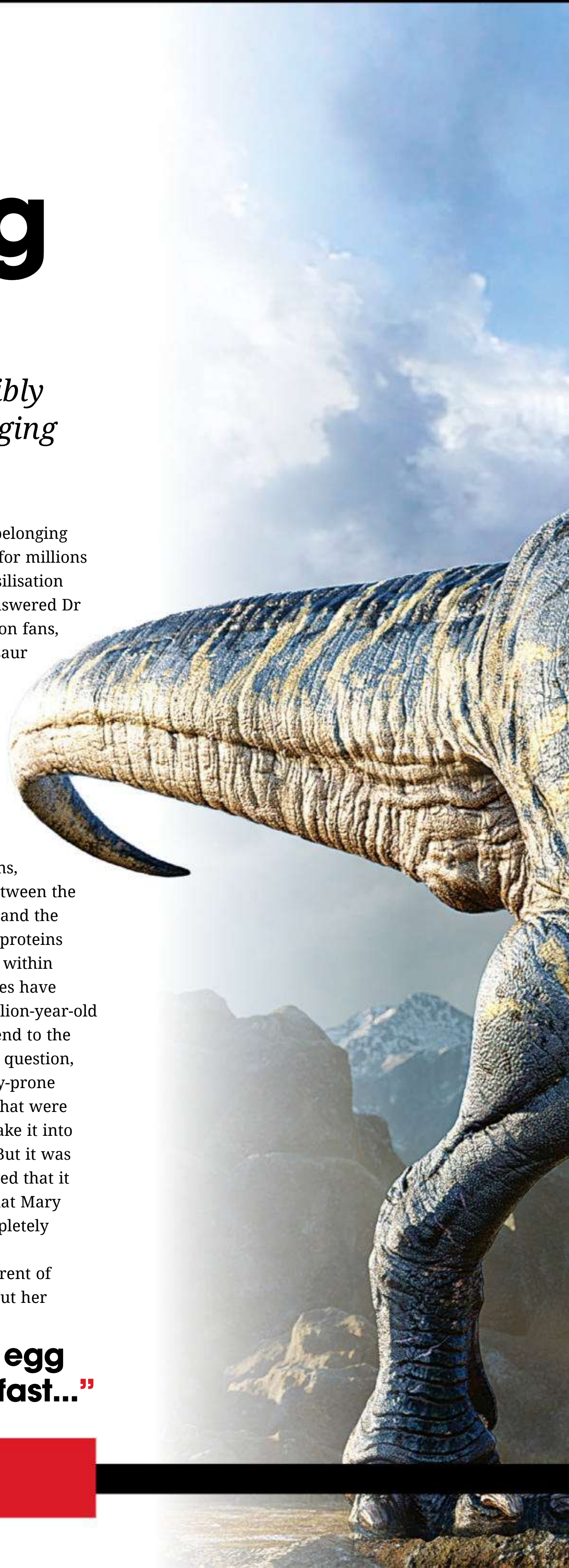
The pictures whipped up a scientific storm. If it could be proved that the round structures Schweitzer had found were cells belonging to a dinosaur that had been dead for millions of years, then our ideas about fossilisation must be wrong. We’d also have answered Dr Sattler’s question. For science-fiction fans, it was just a short leap from dinosaur blood to DNA, and resurrecting a living, breathing T rex. Just rip out the DNA, stick it in an ostrich egg and hey presto! A dinosaur! Right?

Not so fast. As Dr Patrick Orr, a fossil expert at University College Dublin, explains, there’s a difference between the presence of soft tissue and the molecular signatures of proteins and DNA that once resided within that tissue. While Orr’s own studies have unearthed bone marrow in 10-million-year-old rocks, his investigations don’t extend to the chemical constituents. “There’s no question, as far as I’m concerned, that decay-prone tissues, such as the blood vessels that were reported originally, can and do make it into the geological record,” says Orr. “But it was quite clear as the discussion evolved that it was the actual chemical fidelity that Mary was commenting on. That’s a completely separate field.”

Schweitzer, who has faced a torrent of criticism from other scientists about her

Did you know?
700 dinosaur species have been discovered, and more than 100 have been found in Britain

“Just rip out the DNA, stick it in an ostrich egg and hey presto! A dinosaur! Right? Not so fast...”



© Getty

Yutyrannus' fuzzy plumage was an early precursor to modern feathers

Did you know?
T rex's tiny arms were likely used for holding prey

Scaling down the T rex

Could the most iconic dinosaur have been a feathered beast? Not content with robbing the T rex of its upright stance, palaeontologists now have mounting evidence that the world's most famous dinosaur could have been coated not in scales, but in a range of flamboyant feathers. Scientists have long established a link between modern birds and dinosaurs, and in the past 20 years, well-preserved specimens of two of the T rex's closest relatives – Yutyrannus and Dilong – have been found coated in a layer of feathers. This is compelling evidence that feathers were the standard for carnivorous dinosaurs, but if T rex did have feathers they would likely have been sparse – larger animals are in danger of overheating if they have too much insulation. Resurrecting T rex would provide us with the ultimate answer.

molecular analyses, remains sanguine. After subjecting her blood vessels to "a million methods" she can conclude only that what she's finding are dinosaur proteins. On DNA, though, she's a little more cagey. "I don't work on DNA," she says. "I don't have an appropriate lab." Still, in a paper, Schweitzer's team reported how they had tested for DNA, alongside proteins, in cell-like structures from T rex fossils. The study claims to show antibodies sticking to "material consistent with DNA" in the same way they do to ostrich DNA.

So, do we have dinosaur DNA or not? Since palaeontologists generally try to avoid talk of DNA, it's a difficult question to answer. But Dr Jakob Vinther at the University of Bristol is one palaeontologist who is thinking about DNA. He's one member of a 56-strong team that published the genome of a 700,000-year-old horse whose bones were found frozen in

This horse skull, found in Canada's Yukon, dates back 700,000 years

the permafrost of Yukon, Canada. They beat the record for sequencing a genome from ancient DNA by more than 600,000 years.

As Vinther explains, the ancient molecules were badly degraded. "Basically, the DNA had fallen apart," he says. "But we found lots of little fragments, and the fragments were long enough for us to be able to patch them together and then reconstruct the genome of this old horse." They used genome sequences

A team of researchers was able to sequence the horse's DNA from bone marrow

Surviving in a changed world

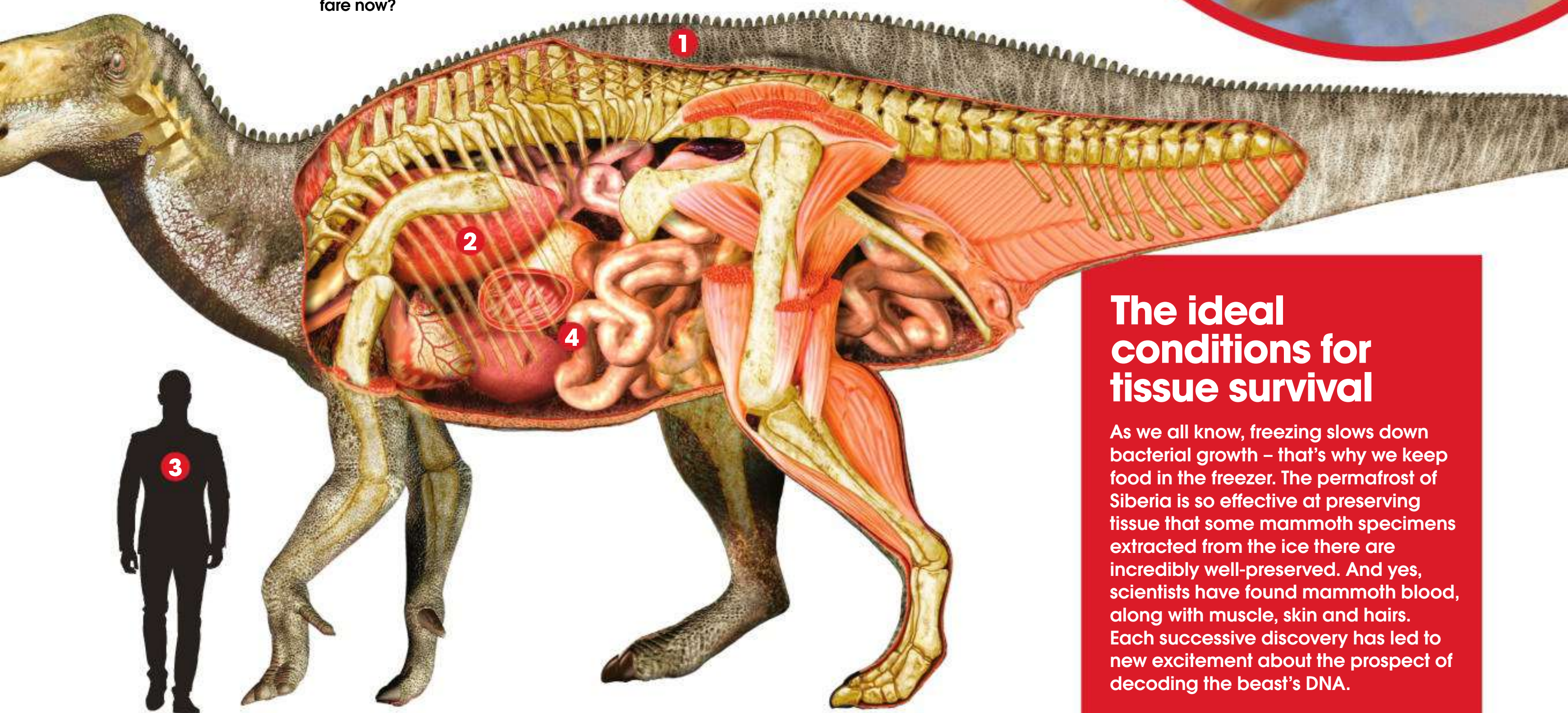
Could dinosaurs live in today's very different conditions?

1 Colder climes During the Jurassic and Cretaceous periods, it was a lot warmer than today. Ice sheets had not yet formed at the poles, which were covered by thick forests. If dinosaurs were cold-blooded, they would likely find our climate too chilly.

2 Lower CO_2 The hot climate of the Cretaceous seems to have been related to high atmospheric carbon dioxide levels. In this period, they were off the scale: 1,000 parts per million versus 400 today. Dinosaurs must have adapted to breathing this stifling air. How would they fare now?

3 New predators Humans are the biggest threat a dinosaur would face. We all saw what happened in *Jurassic Park*. Humans create dinosaurs. Humans enslave dinosaurs. Dinosaurs escape. Humans pull guns on dinosaurs.

4 Different food We can't say what plants dinosaurs ate, but scientists have suggested many didn't chew their food. They swallowed it and let stomach stones or plant-digesting enzymes do their work. Those enzymes would have been adapted to the plants of the era, only some of which survive today.



from modern horse DNA as a template. But piecing together a dinosaur genome would be much trickier – like a puzzle without a picture to work from and no indication of whether there should be 2,000, 20,000 or 200,000 pieces. Besides which, it would mean finding much older DNA, at least tens of millions of years old. So while Vinther thinks Schweitzer has made some fascinating discoveries, he says she's probably over-interpreting her data.

Even Schweitzer is cynical about assembling a complete dinosaur genome. "Even if we had the complete genome, we don't know how many chromosomes dinosaurs had," she says. On its own, the string of code that makes up a genome doesn't tell us anything about how that code is arranged on the chromosomes inside a cell.

The number of chromosomes, Schweitzer points out, is one of the defining aspects of a species. Human DNA is packaged up into 46 chromosomes, and if just one is deleted or duplicated, it can be devastating, hinting at what might happen if we try to force an entire T rex genome – if we could ever get one – into the wrong package.

The ideal conditions for tissue survival

As we all know, freezing slows down bacterial growth – that's why we keep food in the freezer. The permafrost of Siberia is so effective at preserving tissue that some mammoth specimens extracted from the ice there are incredibly well-preserved. And yes, scientists have found mammoth blood, along with muscle, skin and hairs. Each successive discovery has led to new excitement about the prospect of decoding the beast's DNA.

When it comes to keeping tissue intact, the colder the better

So the prospects for a dinosaur resurrection project don't look rosy. Dr Dave Hone, a biologist and dinosaur expert at Queen Mary University of London, says he's not sure why anyone is taking the idea seriously. When we suggest it might be due to a certain science-fiction film, he's quick to reply: "It's a film! I've seen Aliens as well, but that doesn't mean that we've got interstellar ships that are going to start landing on other planets and we should start worrying about whether we need to quarantine them."

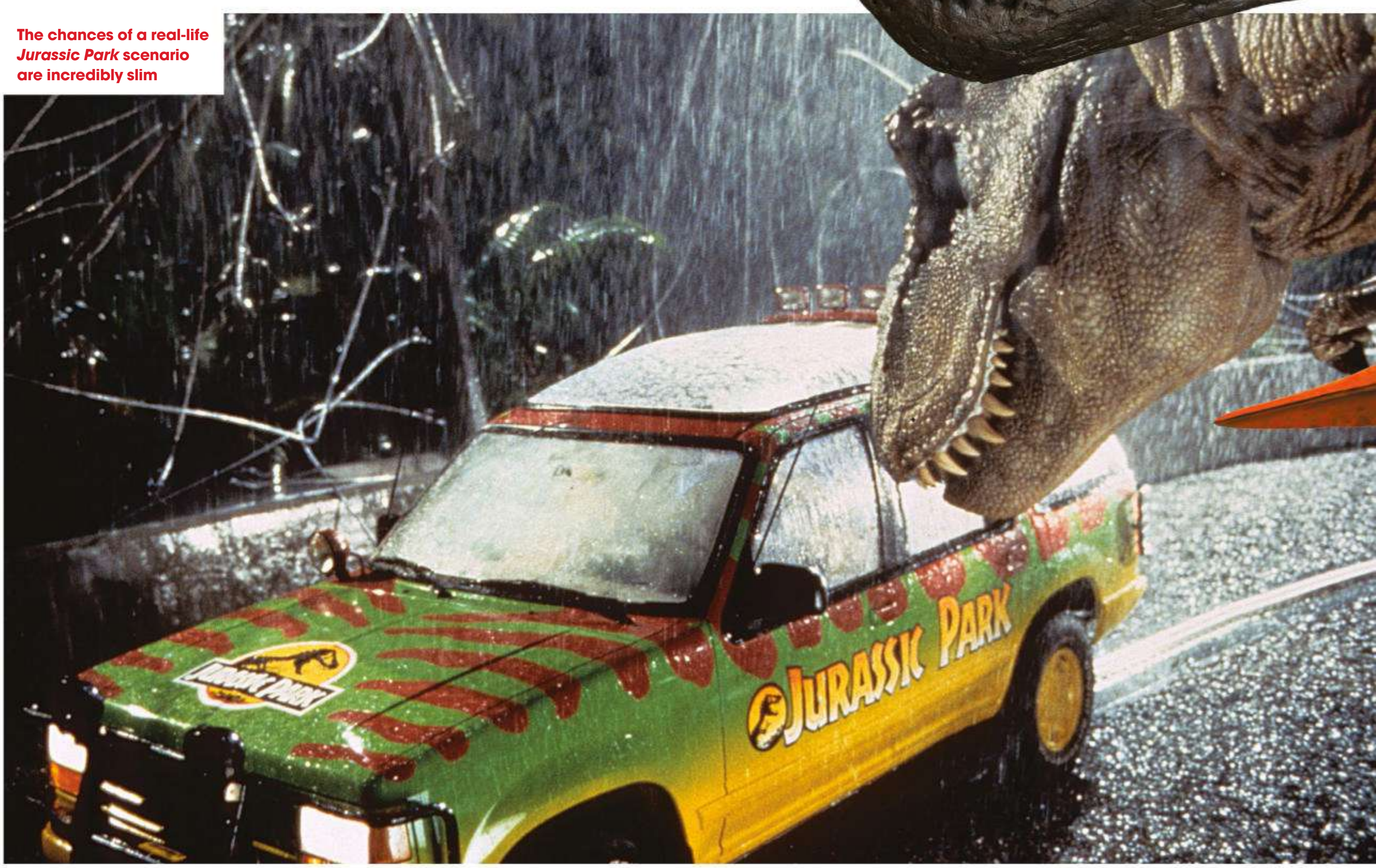
He adds that putting together a full dinosaur genome is just the first in a long line of problems – getting that into a cell and then to grow into an embryonic dinosaur is virtually inconceivable, especially given the gargantuan effort it took to clone a solitary sheep, an animal we're pretty familiar with. About other proposed de-extinction projects, such as the passenger pigeon, Hone is slightly more optimistic. Given that we have passenger pigeons in museum collections and close living relatives in modern pigeons, it's less of a stretch to think about cloning one.

Schweitzer, meanwhile, continues her studies – she's eager to learn all she can about the evolution of dinosaurs, but not, she says, to clone a T rex. "Is it really worth doing if you're only going to bring back one? I mean, it takes 5,000 organisms to make a viable population. Where are you going to get 5,000? And where are you going to put them if you did?"

The T rex would be many people's first choice for resurrection

"Putting together a full dinosaur genome is just the first in a long line of problems"

The chances of a real-life *Jurassic Park* scenario are incredibly slim



Did you know?
One of the first discoveries was the Bristol dinosaur. Thecodontosaurus was found in 1834 and lived 210 million years ago

DNA and preserved mosquitoes

Can we really find dinosaur blood encased in tree sap? In *Jurassic Park*, they didn't get their dinosaur DNA from fossilised bones... They got it from mosquitoes that had gorged themselves on dinosaur blood and then got stuck in tree sap. So why don't we just do that? A study published in the journal *PLOS One* demonstrated why: When trying to extract DNA from two bees entombed in resin – one 10,600 years old and one just 60 years old – University of Manchester researchers failed both times, leading to the conclusion that DNA isn't preserved in insect samples from our own Anthropocene epoch, let alone the reign of the dinosaurs. Their results suggest that previous studies claiming to have achieved the feat were contaminated with microbial DNA.

Dinosaur soft tissue may have been found, but not intact DNA, making it unlikely we'll ever see this scenario come to fruition in real life

EXTINCTION & LEGACY

Could we build a Jurassic Park?

As science advances and new discoveries are made, could we ever actually develop the technology required to bring back the dinosaurs? Let's dive into a thought experiment...

Welcome to Jurassic Park. As we open the gates to this zoo of previously extinct creatures, how would you expect the dinosaurs behind them to look? For those who have read or watched *Jurassic Park*, the image of a dinosaur may have already been planted in your mind. Your perception might be plagued by the gruesome scenes of park rangers becoming easy meals, or the film's iconic theme tune might resonate in your head as you envisage herds of long-necked beasts parading across the land. With great diversity between species, the thrill of this dinosaur park cannot be denied. But what about its accuracy?

When Michael Crichton first conceived the *Jurassic Park* story in the late 1980s, one of the last things he wrote was perhaps the most significant. How would the scientists in the story obtain the DNA needed to create a theme park of dinosaurs? This would be the key to the entire plot, giving the story a feeling of scientific realism. Eventually, Crichton was inspired by a scientific paper he read. The paper referenced a fly that had been found preserved inside hardened tree resin. Somehow, at the end of its life, the fly had ended up submerged in this resin time capsule. This was not just the stroke of genius that led to the creation of this fictional land, but a real-life discovery. Together the story of *Jurassic Park* and the science at the centre of the tale would inspire the next generation of palaeontologists, opening the world's imagination to dinosaurs.

What might fascinate people most about dinosaurs is the multitude of unanswered questions, with only hints at their dominance before our time. What did dinosaurs really look like, and how did their unique appendages assist them as they scoured the land in diverse groups?

As humans have never lived alongside dinosaurs, nobody holds the answers to some of the questions asked by children and adults alike. We continue to learn more about dinosaurs as interest and research grows – and with new fossil finds – and we have now discovered more than 700 dinosaur species worldwide, but as time passes by, it separates these ancient beasts further from us into the past.

Scientists are currently working to reverse extinction by bringing animals that vanished from Earth long ago back into our lives. By editing the genetic code in the DNA of extinct animals' closest living relatives, scientists can slowly build backwards and manipulate a model of the species' DNA.

One of the most high-profile cases of this de-extinction research involves the woolly mammoth, which died out around 4,000 years ago. Their DNA has been found preserved in the frozen soil of Siberia, so some scientists are working on a project to combine these fragments of genetic code with that of living elephants. There might be thousands of years separating these species – and over 60 million years for dinosaurs – but if scientists are successful in producing these extinct species, this could be a stepping stone towards the beginning of a true 'Jurassic Park'.

Did you know?
Scientists have determined that DNA has a half-life of 521 years

Have we found dinosaur DNA?

The biggest hurdle to overcome before we could ever create a dinosaur park is how to source the main ingredient. Without access to intact dinosaur DNA, we are unable to clone true dinosaurs.

New fossils are being uncovered from the ground every day. However, while this can provide important evidence of a species' form, its organic material has long disappeared. Instead of bone is the rock and sediment that has filled its place. While these clues can tell us about a specimen's shape, size, the time it was alive and any unique features that the animal had, it is unable to give us the crucial genetic information.

In 2020, researchers from the US and China discovered cartilage that they believe to contain dinosaur DNA. Many palaeontologists are incredibly sceptical about this claim, as it is widely believed that it's impossible for the protein in these molecules to survive for millions of years. The cartilage, from the Hypacrosaurus species of the Cretaceous Period, is over 70 million years old, but has been calcified and fossilised, which may have protected the inside of the cells.

Bones can survive for millions of years, while soft tissue is the first to break down

Cloning dinosaurs

Follow the method seen in Jurassic Park *to extract dinosaur DNA and decipher the true science from the fiction*

1 The trapped mosquito

Amber is fossilised tree resin, which has been known to preserve small organisms. To become preserved, an insect would have to have died as the resin hardened around it, or have been completely covered in the resin soon after its death. Buried in sediment, resin hardens under the extreme pressure and heat. Amber dehydrates the organism inside, which helps to slow its decay. It also serves as a protective shell, and as it hardens creates a perfect imprint of what's trapped inside.

Insects are small enough to be encapsulated, but how would a dinosaur's DNA end up in this resin? The idea behind the mosquito in *Jurassic Park* is that only the genetic material from the dinosaur needs to be preserved. Mosquitoes existed at the same time as dinosaurs, and it's possible that a mosquito with dinosaur blood inside it could have become trapped in resin. However, over time blood will decompose, and scientists have found that this material doesn't preserve DNA as well as harder outer tissue.

Did you know?
The oldest known sample of amber was found to be 320 million years old

2 Cell survival

Bones and teeth are relatively common finds when it comes to dinosaur hunting. But what about the soft tissue needed for cloning? Soft tissue, containing gene-packed living cells, is the first thing to vanish when fossils are forming. Palaeontologists used to accept that the survival of any soft tissue over the course of millions of years was impossible, but in recent years unlikely discoveries have suggested otherwise. In 2005, Mary Schweitzer discovered small amounts of protein inside the leg of a T rex in Montana. This showed how new discoveries can redefine what is possible.

3 Making a strand

In order to clone an animal with all the same physical features, a complete genome needs to be retrieved. For animals that are still alive, or died out more recently, collecting this information can be simple. Any potential dinosaur DNA that has been discovered at present has been in small fragments. This is due to a combination of ultraviolet light, cosmic radiation and enzymes breaking down proteins.

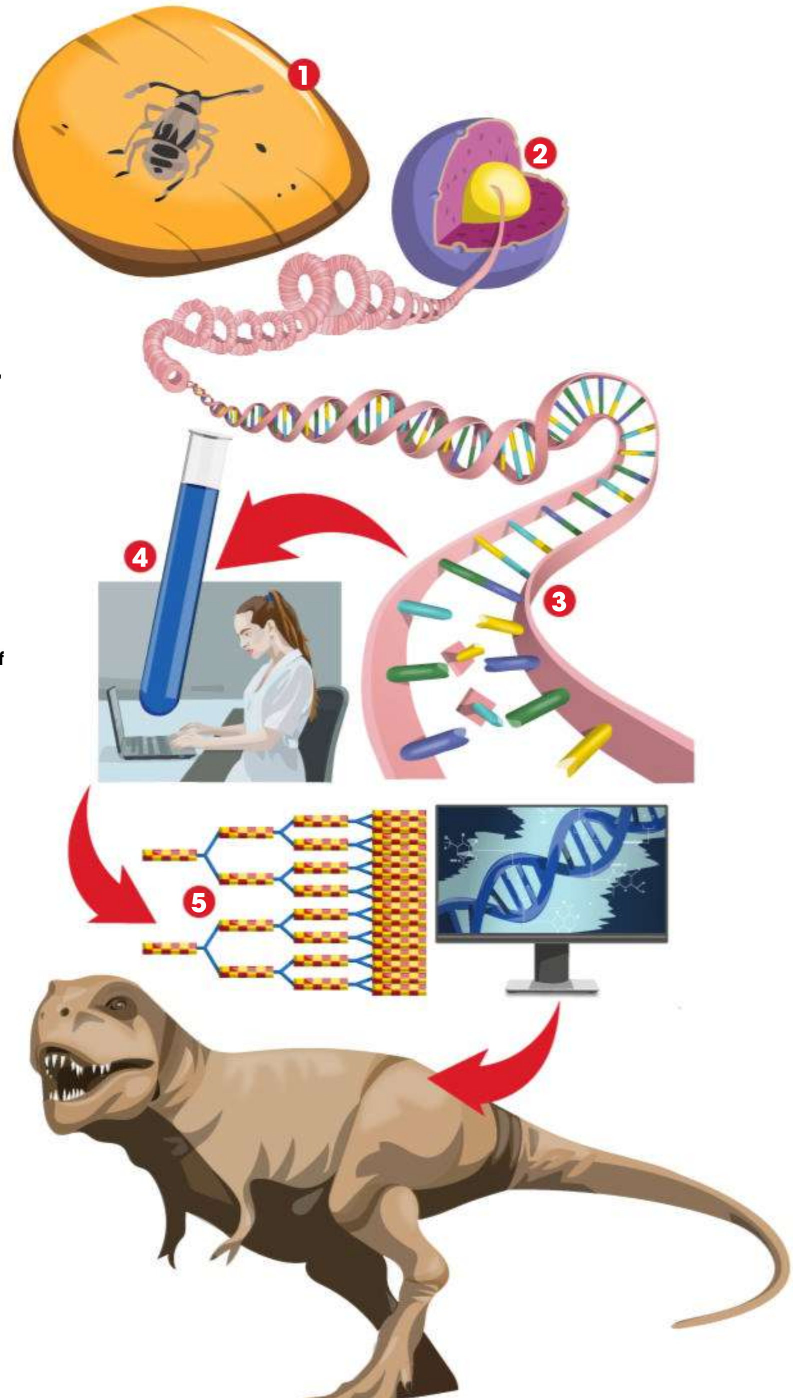
4 The frog addition

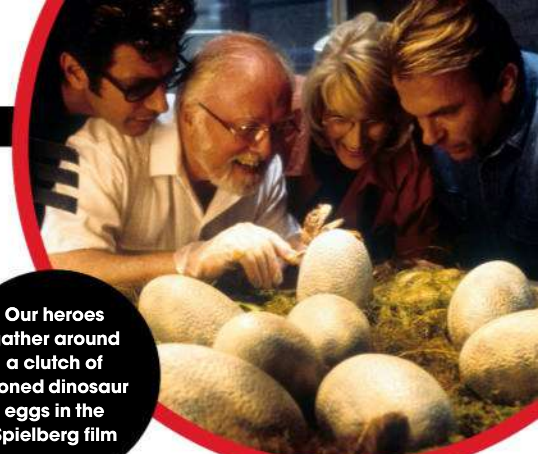
As the DNA source is unlikely to be complete, is there any way of replacing the material that has been lost? Without further supplies of dinosaur DNA, the story of *Jurassic Park* involves replacing missing fragments with frog DNA. The use of frog DNA was vital to the plot for population control. Some frog species can undergo a biological change from female to male in order to breed when their species is under threat. This trait was passed to the dinosaurs.

In reality, as frogs are amphibians, they are entirely different to dinosaurs, and their DNA is nowhere near similar enough. Birds, on the other hand, are descended from dinosaurs, and may have significant similarities. The best hope for palaeontologists who want to bring back dinosaurs is to wait for a well-preserved, large DNA sequence to be found.

5 Creating copies

One method that can be used to create multiple copies of small DNA fragments is a polymerase chain reaction. Using a heat-resistant enzyme, a strand of DNA can be copied, producing millions of identical strands and providing a sample large enough for the order of amino acids to be analysed and sequenced.





Our heroes gather around a clutch of cloned dinosaur eggs in the Spielberg film

Q&A

Jack Horner

Jurassic Park's scientific advisor has plans to make a pet dinosaur

Horner is the real palaeontologist who inspired the character of Dr Alan Grant in *Jurassic Park*. Since finding his first dinosaur bone at the age of eight, Horner has dug up the first dinosaur embryos, the first dinosaur eggs in the Western world and has discovered and named the dinosaur species 'Maiasaura'. During his time as the palaeontology consultant for the *Jurassic Park* films, Horner advised Steven Spielberg on how to make the portrayal of dinosaurs as realistic as possible. While he deems the cloning process pure fiction, this hasn't stopped Horner from trying to bring back the dinosaurs

How would a Jurassic Park need to be changed in real life?
If you really, seriously want to build a Jurassic Park and are not just making a movie, you want walls around the dinosaurs to keep them in. Reinforced concrete is going to work a lot better than electric fences, because electricity can go out. Electric fences were not a very good idea.

In reality, could any of the cloning processes seen in the film work?
We think we have found signals for DNA and that there might be tiny bits left, but not enough to use to make a dinosaur. We can get collagen and some dinosaur proteins, but not all the material we need. If we had the DNA, it would be ridiculous to put it in an ostrich egg. The thing to do would be to grow it in a test tube, because we have no idea how big the embryos of all dinosaurs are. Some dinosaur eggs are the size of ostrich eggs, but for a Tyrannosaur, we think they are a lot longer and they're bigger. It's like thinking about putting a human embryo inside a squirrel. If we're going to make a dinosaur, it's not going to be in the same way as *Jurassic Park*. That doesn't mean we can't make one. I actually have a laboratory where we are attempting to figure out how to make a dinosaur.

How are you trying to create a dinosaur?
It's called the dino-chicken project, and it's mostly based on genetic engineering. The idea is to use atavistic genes. They are basically ancestral genes, meaning that ancestral animals programmed certain features. For instance, occasionally children are born with extra vertebrae and form a low tail, which the doctor just picks off when the child is born. And every once in a while snakes are born with little appendages. Whales evolved from land animals, and occasionally they are born with extra limbs sticking out the side of themselves. These are atavistic genes. They were useful at one time, but through the course of evolution they have been turned off. Occasionally they are accidentally turned back on, and snakes get a set of legs.

I was hoping that some of the features of a dinosaur were atavistic in a bird. All bird species are related to one another, with one common ancestor – dinosaurs – so any bird should work. Chickens are the easiest thing to get eggs from, so I built a laboratory, hired some geneticists and developmental biologists and started seeing if we could find some of these potential atavistic genes.

Why did you start this project?
I'd like to have a pet dinosaur. Wouldn't everybody like to have a pet dinosaur? I have a pet bird, but that's the closest I can get right now. When I started the project, everybody thought it was just crazy. But then, after a little while, other laboratories started working on it, like Yale University and McGill University, and they started finding some atavistic genes. We've been working on the tail, mostly, because that seems to be the hardest part.

Is your method working?
We discovered that the reduction of the tail from long-tail dinosaur to a short-tail bird is not an atavistic gene. We are trying to figure out how the tail actually works and reverse the process that formed the short tail. Other laboratories have looked at the face, teeth, arms and hands. I think we can do pretty much all the rest of the body. We have the potential of making an animal that has a dinosaur-like head, probably with teeth in it, and we certainly have the capability of reversing the wings to make arms and hands. We know we can do that, but right now we're just trying to fix the tail.

"We are attempting to figure out how to make a dinosaur"

If you succeed, would you make something similar to a Jurassic Park?
That's a whole different thing. People always say, 'where are you going to put these dinosaurs when you make them', and I always say that many thousands of years ago we started with wolves, and now we have Chihuahuas. Dogs are basically wolves, and we don't really have to contain them. I wouldn't expect dino-chickens to be the same as the dinosaurs in *Jurassic Park*. They're going to be domestic animals that we don't have to worry about. If you were cloning a real Tyrannosaur, you would have to worry about containing them. Dogs and cats were wild, but now we don't have to contain them – not to the point of making a park anyway.

A tiny embryo in a test tube. A genetically engineered dinosaur would start like this

Creating the park

How would dinosaurs acclimatise to their new era and neighbours?

Substantial fences

Concrete or steel alone would be too weak to resist the power of a raging dinosaur. Reinforced concrete contains a lattice of steel inside to absorb the stress of any large impacts. It is also a versatile and fire-proof building material

Tropical location

It's been determined that when dinosaurs roamed the Earth, the global temperature would have been around four degrees Celsius higher than it is today. An island in a tropical region of the globe would provide temperatures that many dinosaurs would be comfortable living in

Electric control

Relying on electric fences for the entire park would be too risky to keep the dinosaur population under control. Any electricity shortage would result in large carnivorous dinosaurs being able to escape. They could be beneficial and safer to use for smaller plant-eating dinosaurs, however. This mechanism would work to deter the animals from crossing this line after they associate contact with the fence with the pain of an electric shock.

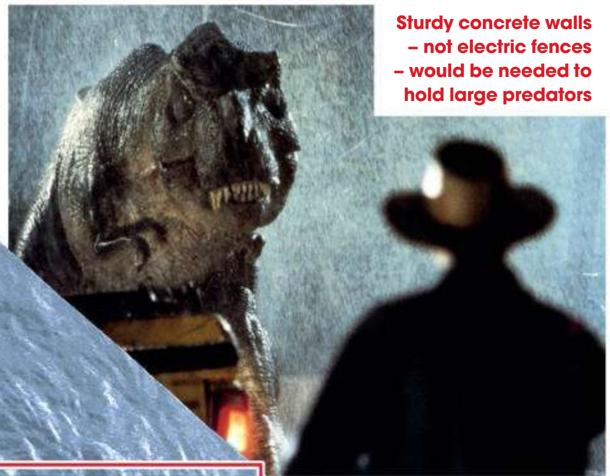
Herbivores

It's likely that many plant-eating dinosaurs would be able to live in the same enclosure in relative harmony. There is evidence of some species living in herds, and so fights between or within herds for better social positions might be observed

A tropical island with varied environments, like Costa Rica, would be a suitable place to keep dinosaurs

Smaller carnivores

The best way to ensure that the species brought into the park had the best chance of survival would be to separate the carnivores into groups that would have lived alongside each other during their reign. Without doing this, you would find that the evolutionary adaptations of some species no longer gave them an advantage



Sturdy concrete walls – not electric fences – would be needed to hold large predators

Large carnivores

For large carnivores such as the Tyrannosaurus rex, it would be important to provide them with significant space to roam and search for food. They should be kept in their own enclosure, as they could fight to the death if paired with similar-sized carnivores.

Plant variety

Most plant-eating dinosaurs are believed to have had flat teeth, ideal for tearing leaves off trees and grinding down plants. Tall, leafy plants would be needed for the long-necked herbivores, while shorter shrubs would benefit those relying on food closer to the ground

Aviary

With wingspans over seven metres, species such as the pteranodon could not be contained on an open island. In order to limit the movement of flying species, a large, dome-shaped enclosure would be needed

Atmosphere adaption

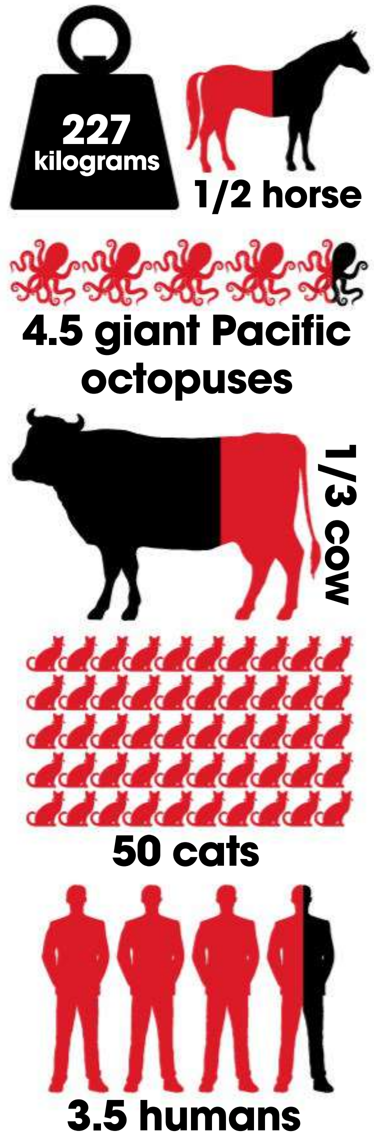
Some studies of air trapped in amber show that its composition during the Cretaceous Period may have been 35 per cent oxygen, as opposed to today's 21 per cent. However, during the dinosaurs' extended time on the planet, this number is believed to have varied substantially. Some species would be better suited to our air than others

Did you know?
Dinosaurs survived on Earth for over 150 million years, while great apes have lived for 6 million years so far

"With great diversity between species, the thrill of this park cannot be denied"

A bite to eat

How much food could an adult T rex consume in one mouthful?



Living with dinosaurs

If dinosaurs hadn't gone extinct, humans are unlikely to have been able to evolve. During the 150 million years that dinosaurs existed, mammals lived alongside them, but these animals were nocturnal and lived in burrows. This suggests that this was the only way for mammals to thrive alongside dinosaurs, emerging mainly at night to hunt. Because our lives are completely separate to that of dinosaurs, there's no way of knowing what would happen if dinosaurs were to live on the same land as us.

By observing human behaviour with today's large predators, it seems unlikely that the two species would live naturally together. Humans take up so much space on the planet that introducing predators like dinosaurs outside of captivity would result in a battle for land.

Introducing meat-eating dinosaurs to Earth would give humans a natural predator

UNDERSTANDING Dinosaurs

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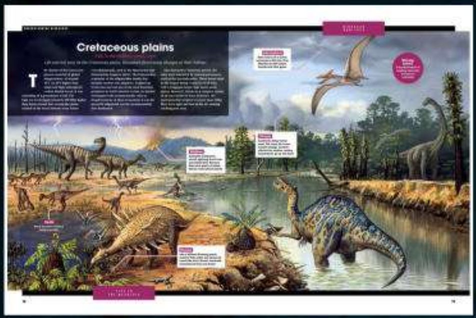

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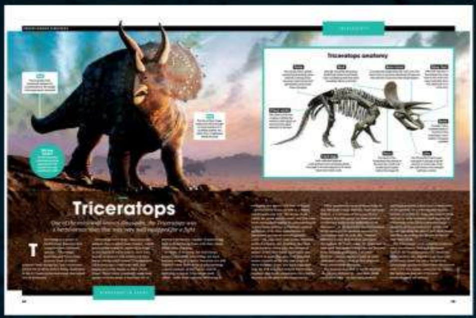

DINOSAURS IN FOCUS
From the terrifying T rex to the towering sauropod titans

EXTINCTION & LEGACY
Piecing together the evidence to explain the dinosaurs' fate

UNDERSTANDING Dinosaurs

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