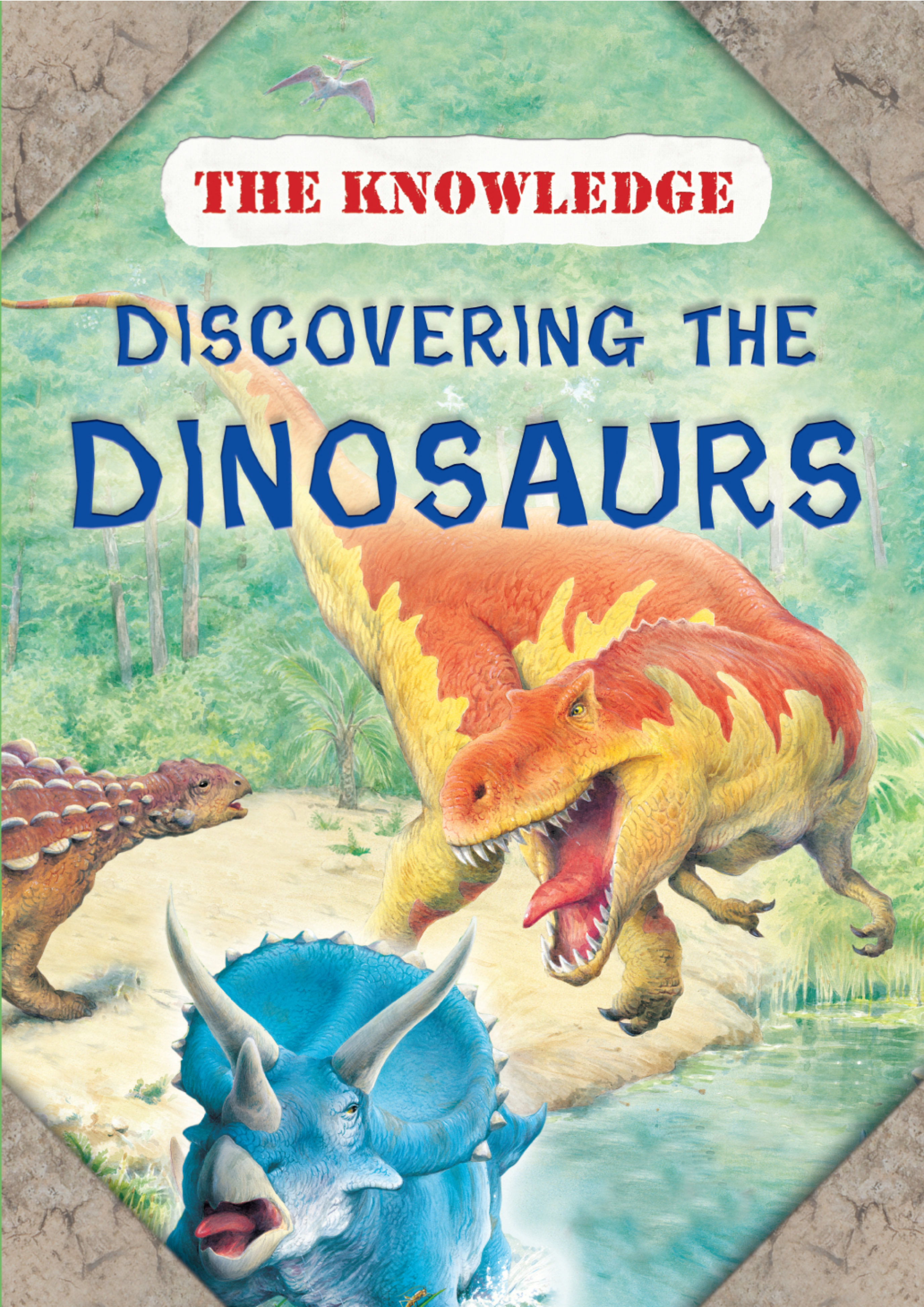
THE KNOWLEDGE

DISCOVERING THE DINOSAURS



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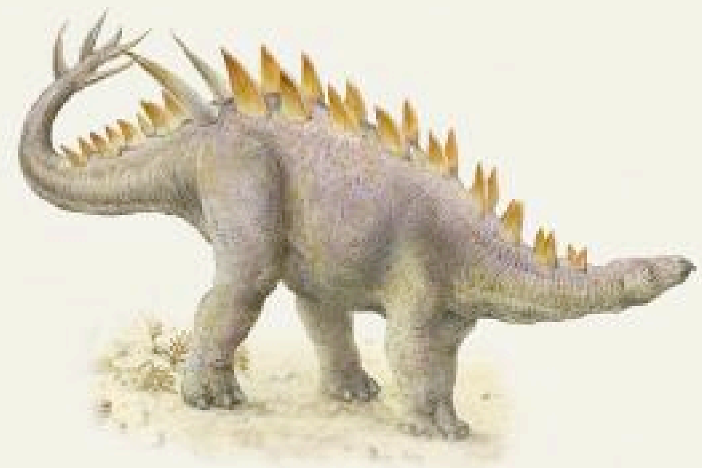

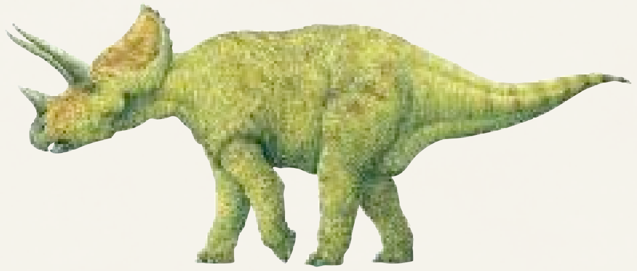

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THE KNOWLEDGE

DISCOVERING THE DINOSAURS

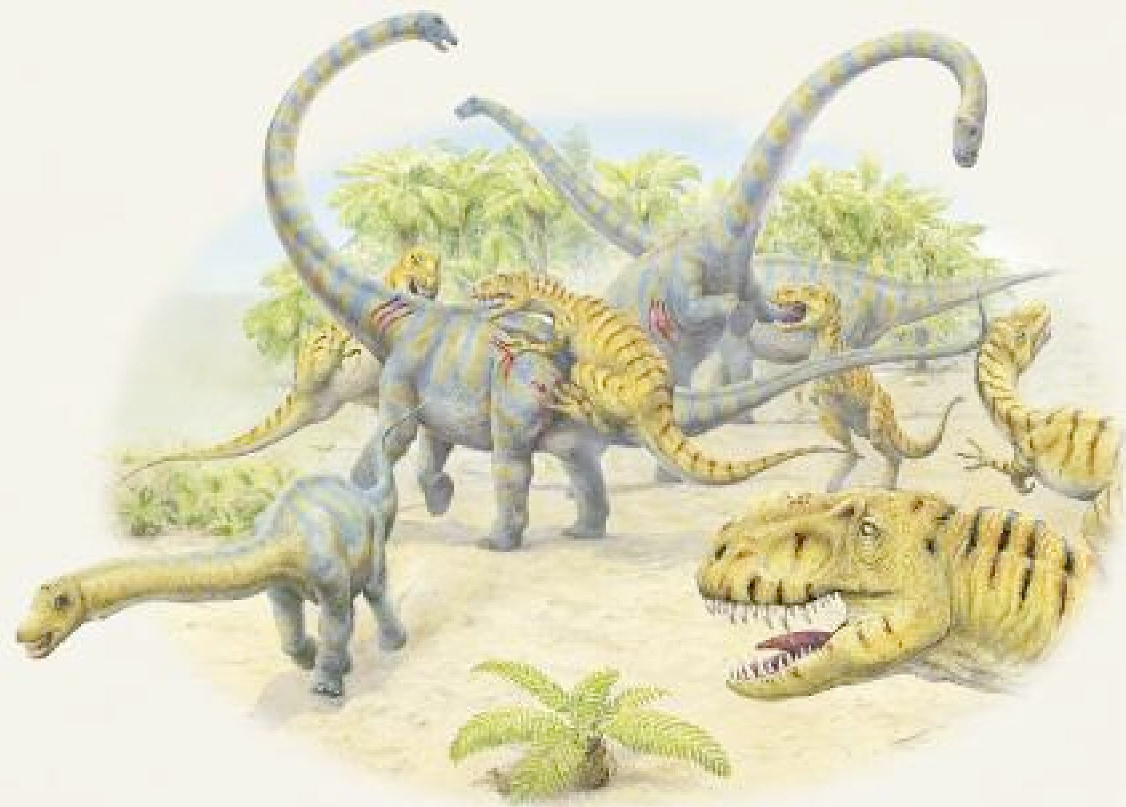
Orpheus

Contents

Introduction

YOU HAVE BEEN appointed to carry out an investigation into how the dinosaurs lived. But how will you go about this? Where will you find your evidence? And what can you learn from it, or deduce from the way other animals behave today? There is also the mystery surrounding the sudden disappearance of the dinosaurs about 65 million years ago...

First, you will need to know all about fossils – the main source of evidence about the dinosaurs – from how they form, to what they can tell us about the dinosaurs. Once you have found a fossil, you will need to excavate it and bring it back to a laboratory for study. Then you can finally start to learn about how the dinosaurs fed, moved and fought. Finally, look at all the evidence to work out what really drove the dinosaurs to extinction.



▲ During the Earth's early years, water poured from the skies for millions of years, creating the oceans.

1. Earth history

BEFORE INVESTIGATING how the dinosaurs lived, you need to know a little about the history of the Earth. You must understand how rocks and fossils formed, and how the natural world has changed over millions of years. It is also good to know what palaeontologists, scientists who study prehistoric life, have already learnt about the story of life on Earth, including when and how the dinosaurs lived.

Like all the planets, the Earth was formed about 4600 million years ago. In its early years, it had no water or life, just barren rock. But volcanoes blasted out gases from beneath its surface. One of these gases was water vapour. Clouds formed and, later, rain fell. It rained for millions of years until basins of land filled to become the oceans. The first living things on the Earth appeared in the oceans about 3500 million years ago.

First life

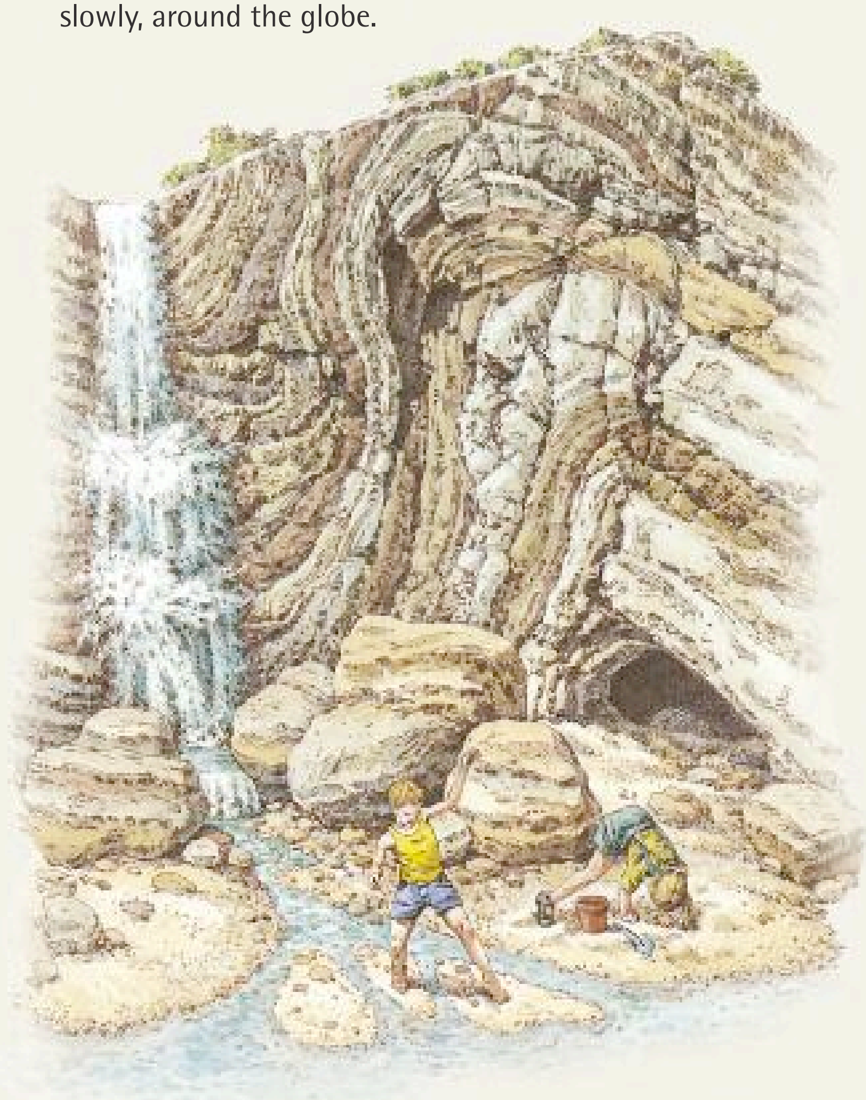
No-one knows how life began, but scientists think that shallow, warm-water pools at the edge of oceans would have been the ideal environment for the formation of chemicals that would eventually become the building blocks of life. The earliest life-forms were the very simplest kinds: bacteria. The oldest fossils are known as stromatolites, bands of blue-green algae that grew in the shallows.

Geological time

Events in the Earth's history are measured in geological time: spans of tens, or even hundreds, of millions of years. Geological time is divided into periods *(see page 8-9).* The dinosaurs lived during three periods, the Triassic, Jurassic and Cretaceous, known as the Age of Dinosaurs. Life began more than 3000 million years ago. Since then, many different kinds of plants and animals have evolved and died out. The Earth, itself, has changed too. Mountains have been pushed up and worn down. Even the continents, the Earth's great land masses, have drifted, very slowly, around the globe.

Recent history

A "recent" event in geological time might be, for example, the current Ice Ages that peaked about 20,000 years ago when ice caps extended over the continents of the Northern Hemisphere.



◀ Sedimentary rocks are made from tiny fragments of other rocks, such as sand, silt or mud. Over geological time, these fragments were pressed and cemented together to form new layers of rock, one on top of the other, called strata. Generally, younger strata lie on top of older ones, but this is not always the case: over time, continental drift and mountain building may have folded or tipped up the strata as in this image.

Timeline of Earth history

Era	Period	Epoch	Began (millions of years ago)	Events
Cenozoic	Quaternary	Holocene	0.0117	★ Modern humans evolve ★ An ice age begins, interrupted by warmer periods
		Pleistocene	2.58	
	Tertiary	Pliocene	5	★ Mammals replace reptiles as the dominant land animals ★ Mammals evolve separately on their own island continents ★ The world becomes cooler, causing tropical forests to be replaced by grassy plains
		Miocene	23	
		Oligocene	34	
		Eocene	56	
		Palaeocene	65	
Mesozoic	Cretaceous	Late Cretaceous	89	★ The dinosaurs become extinct at the end of the Cretaceous ★ Flowering plants evolve ★ Most sauropods die out ★ Ornithopods evolve
		Middle Cretaceous	130	
		Early Cretaceous	146	
	Jurassic	Late Jurassic	161	★ Pangaea begins to break up ★ Giant sauropods and large, powerful theropods evolve ★ Feathered dinosaurs and birds evolve ★ Ornithischian dinosaurs evolve
		Middle Jurassic	176	
		Early Jurassic	200	
	Triassic	Late Triassic	228	★ The first dinosaurs and pterosaurs evolve ★ The first large marine reptiles evolve ★ The first mammals evolve ★ Ferns dominate Triassic plant life
		Middle Triassic	245	
		Early Triassic	251	
Palaeozoic	Permian		299	★ Pangaea forms ★ The first archosaurs evolve
	Carboniferous	Pennsylvanian	318	★ The first reptiles evolve ★ Hot, steamy coal swamps cover tropical regions of the Earth
		Mississippian	359	
	Devonian		416	★ The first amphibians evolve ★ The first lobefin fish evolve
	Silurian		443	★ The first plants with roots evolve ★ The first fish with jaws evolve
	Ordovician		488	★ The first land plants evolve ★ The first fish evolve
	Cambrian		542	★ An "explosion" of life: many new life-forms evolve
Precambrian	Proterozoic		2500	★ The first animals evolve
	Archaean		3800	★ The earliest life-forms, bacteria, evolve
	Hadean		4600	★ Formation of the Earth

How fossils form

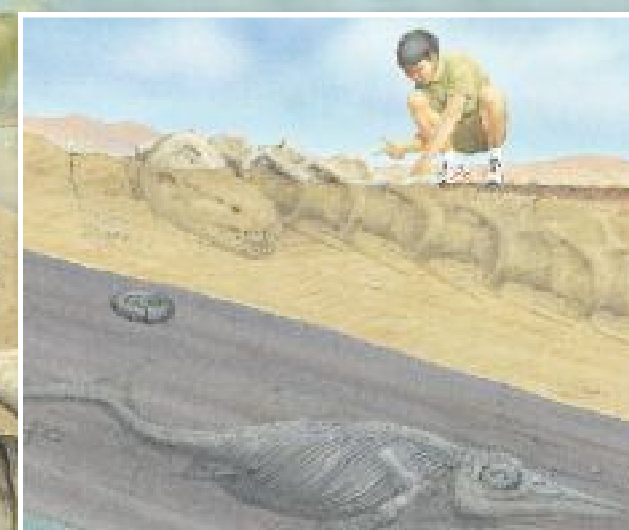
Fossils are the remains of once-living things preserved in rock. The soft parts rot away, usually leaving no trace, but hard parts, such as teeth, bones, claws and shells, sometimes remain. When buried under sediments in water, they are slowly replaced by minerals in the sediment or carried in the water: they become part of the rock. The remains of animals and plants that lived at the same time become fossilized in the same rocks. So scientists can use fossils to work out what life was like at different times in the past.

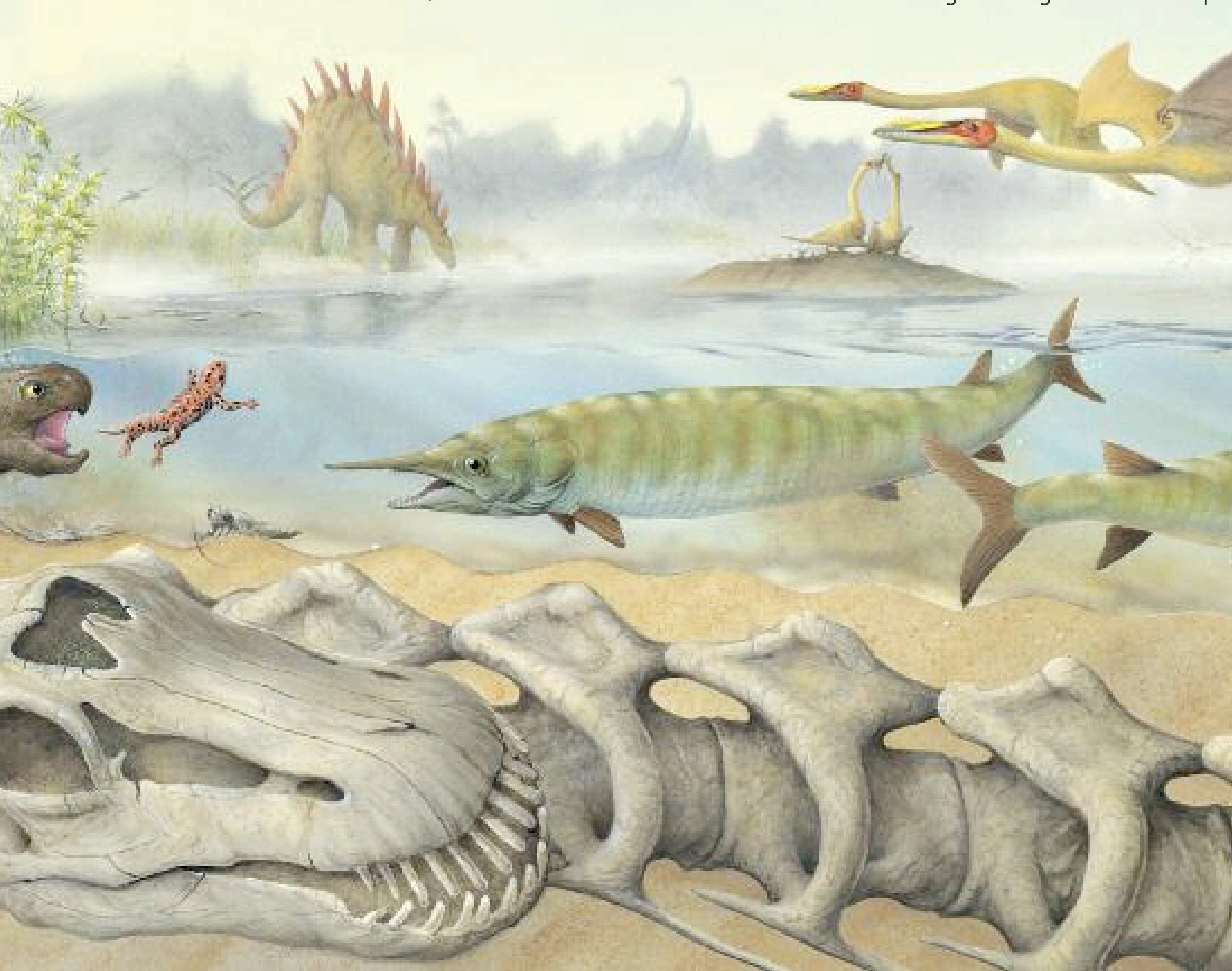
1 Fossils form when a dead creature is quickly buried in sediment such as mud, sand or silt, for example, on a riverbed or in the sea. Here, a sauropod, *Mamenchisaurus*, is caught in a flash flood and drowns in the torrential water.

Eggshell, skin or feather impressions, droppings and footprints are known as trace fossils. They can be just as revealing as true fossils – especially helpful in describing a dinosaur's lifestyle, for example. The soft parts of living things, including, for example, an animal's internal organs or skin, are usually eaten by scavengers or rot away before fossilization begins. But, if the dead organism is buried rapidly in soft sediment, like mud, with little or no bacteria present, then it is possible that the soft parts can become fossilized as well. Such fossils are extremely rare. One example is the Solnhofen beds of southern Germany, where plants, feathers and even the wings of dragonflies are all preserved.

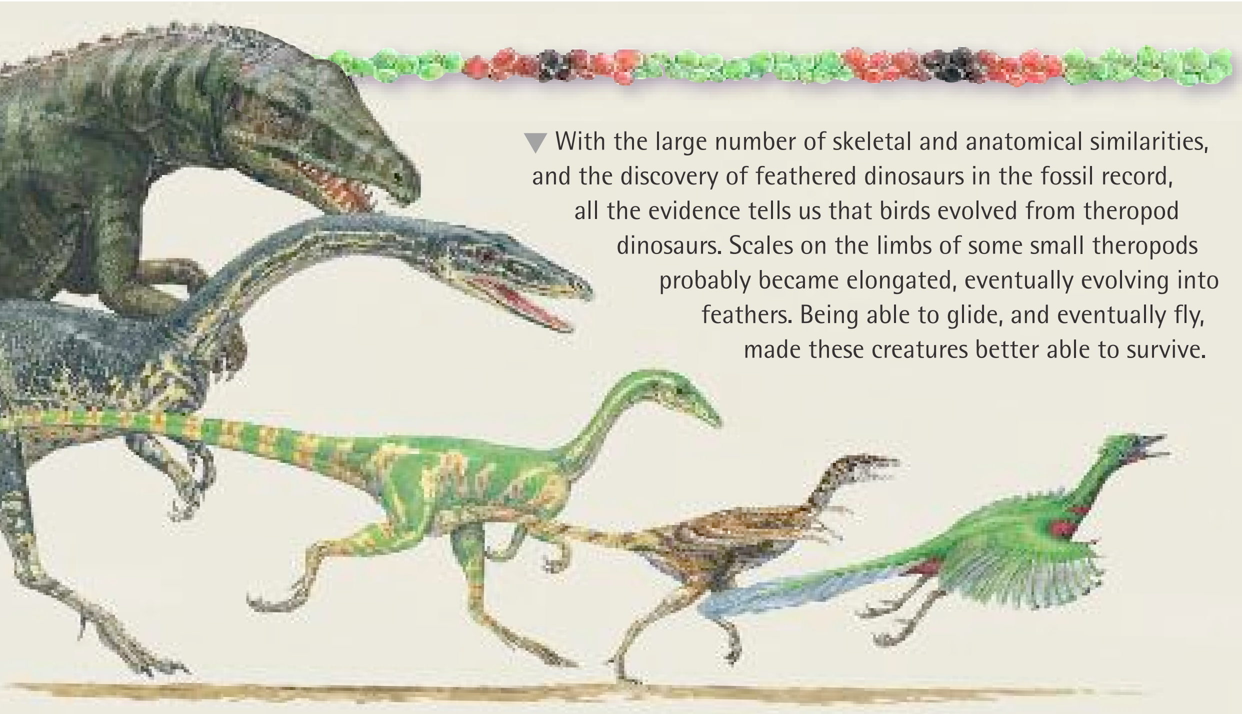
3 As the sediments around the skeleton turn to rock, water and the minerals dissolved in it seep into the pores in the bones. Gradually the bone is replaced by the minerals and becomes part of the surrounding rock *(below).*

4 The exact shape of the original bones remains the same. Over millions of years, other rock layers build up above it. The layers are often tilted or folded due to Earth movements. If the layer containing the fossil dinosaur comes to the surface, perhaps as the result of erosion, the fossil may be revealed and discovered *(below).*

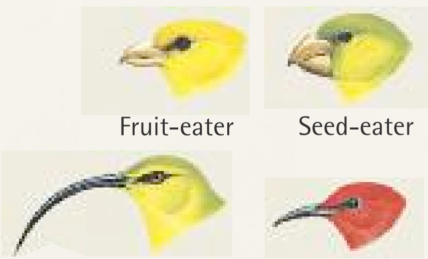




2 The soft parts, such as the skin, flesh and organs rot away. The teeth and bones are quickly cloaked in mud and sand, keeping out oxygen and so also bacteria, which would cause decay.



▼ With the large number of skeletal and anatomical similarities, and the discovery of feathered dinosaurs in the fossil record, all the evidence tells us that birds evolved from theropod dinosaurs. Scales on the limbs of some small theropods probably became elongated, eventually evolving into feathers. Being able to glide, and eventually fly, made these creatures better able to survive.

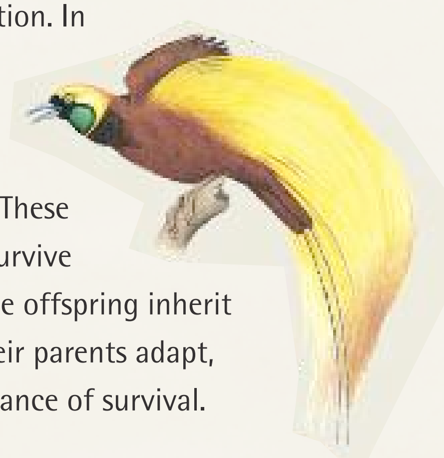


▲ A small flock of finches of a single species once flew to Hawaii. They survived by eating different foods such as fruits, seeds, insects and nectar. Their beaks adapted to obtain each food source. Slowly, the single finch species evolved into many.

Evolution

Over geological time, the fossil record tells us, animals have, very gradually, changed. They may have grown a fin or a tail, developed wings, or lost teeth — all part of a process by which an animal adapts to its environment. This process is known as evolution.

Why does evolution happen? Living things that win the struggle to survive are those best suited or adapted to the conditions they live in. However, these conditions change naturally with time. Some kinds of food may become more scarce. The climate may change. Living things must evolve to suit these new conditions or die out. Evolution happens by the process of natural selection. In order to survive in the wild, some living things become better adapted to the conditions than others. These animals are more likely to survive and produce offspring. If the offspring inherit the features that helped their parents adapt, they, too, will have more chance of survival.



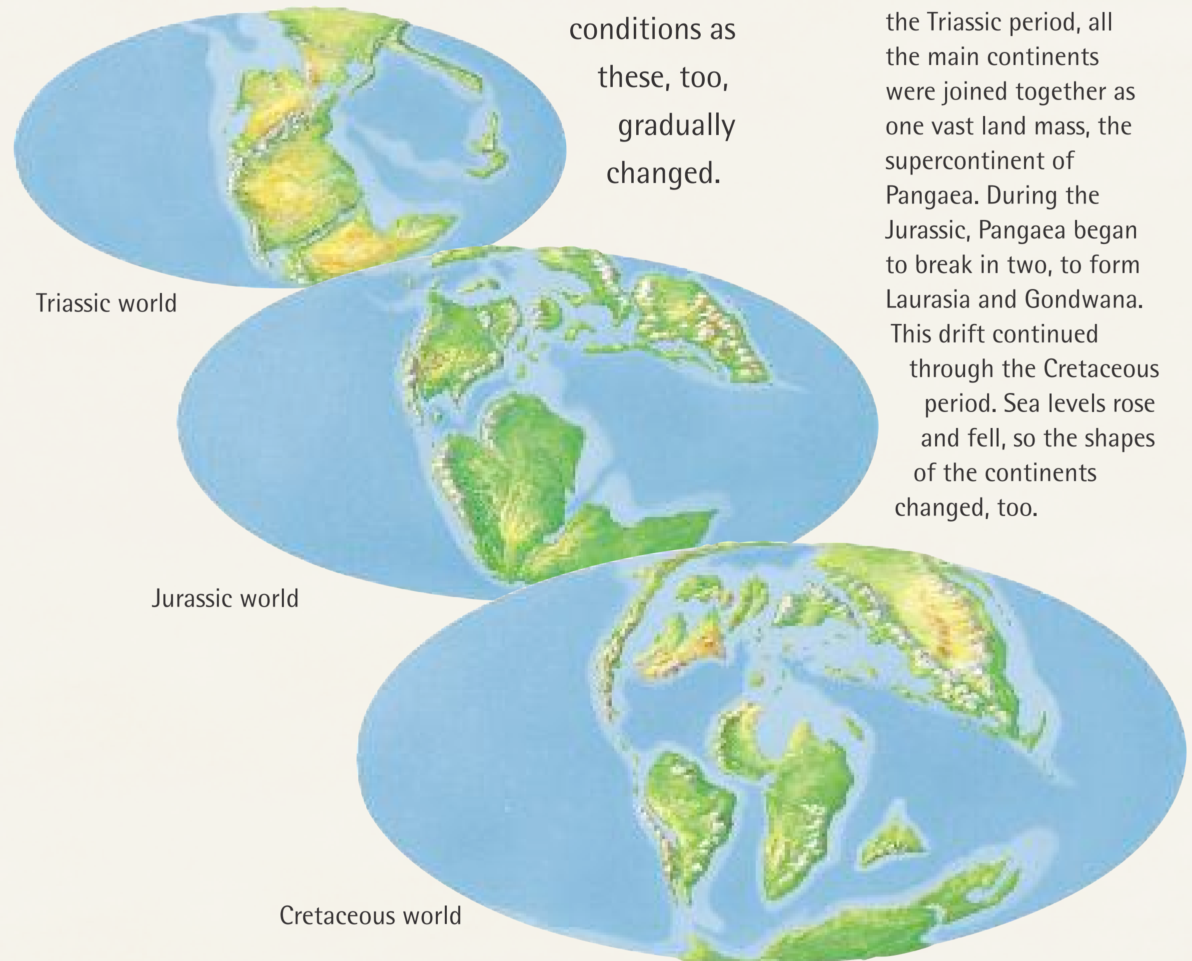
▶ The long, colourful feathers of a male bird of paradise make him more obvious to predators. But they also attract females for breeding, and so this useful feature is passed on to his offspring. Natural selection improves the chances of survival.

Continental drift

Earth's outer shell is divided up into large slabs, called tectonic plates. These plates, which include both the continents and the floors of the oceans, shift about very slowly. This is called continental drift.

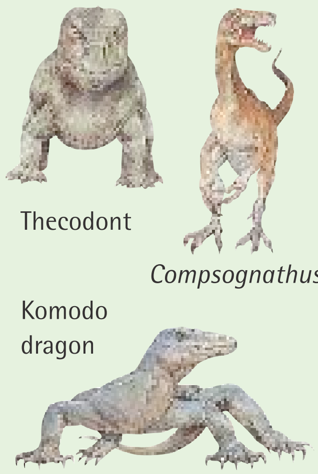
Over geological time, entire continents have drifted around the globe, pushing into, pulling apart from, or sliding alongside one another. These movements have had far-reaching consequences for the evolution of animals. Land-dwelling creatures, such as the dinosaurs, could not cross oceans that opened up as the continents began to drift apart during the Jurassic period. Over time, they began to evolve in different ways to other members of the same family, to suit the new conditions as these, too, gradually changed.

▼ Fossils provide evidence for continental drift. The discovery of fossils of *Lystrosaurus*, a Triassic reptile, in South Africa, Antarctica and India, proves that these lands were once joined together. How else could this land reptile have lived in all three places?



▼ These maps show how the world changed through the Age of Dinosaurs. At first, in the Triassic period, all the main continents were joined together as one vast land mass, the supercontinent of Pangaea. During the Jurassic, Pangaea began to break in two, to form Laurasia and Gondwana. This drift continued through the Cretaceous period. Sea levels rose and fell, so the shapes of the continents changed, too.

2. What is a dinosaur?



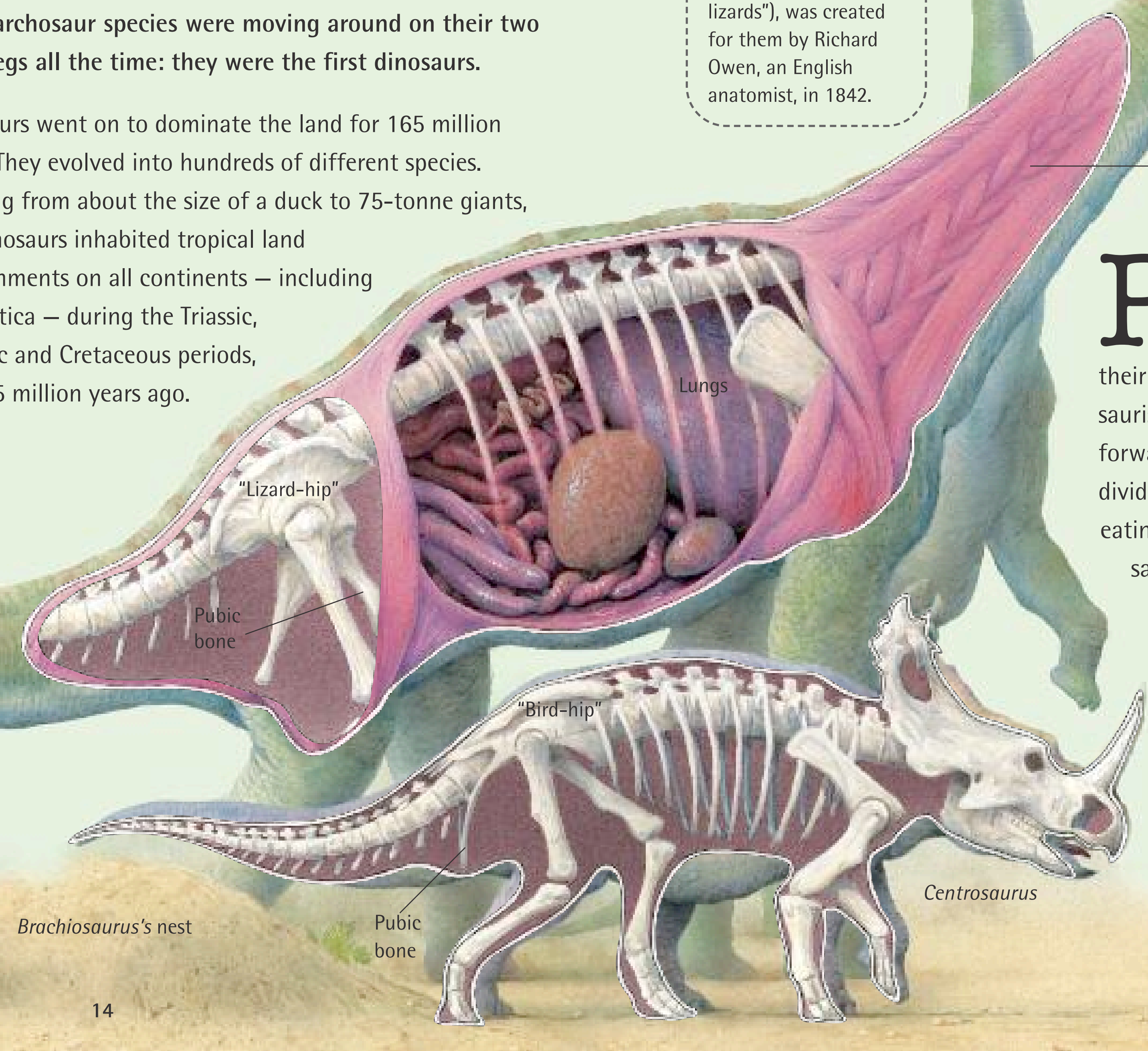
▲ The chief feature that distinguished dinosaurs from other reptiles was their erect posture. Modern lizards, like the Komodo dragon, walk with a sprawling gait. The bone structure of a dinosaur's limbs was more like that of a mammal's. It allowed dinosaurs, such as *Compsognathus*, to walk and run more efficiently. Thecodonts were early archosaurs: they had partly bent legs.

DINOSAURS EVOLVED from archosaurs, a group of reptiles with powerful jaws and bony armour. Early archosaurs had a low, sprawling gait, like that of modern lizards, but later, some kinds began to adopt a more upright posture. By the late Triassic period, some archosaur species were moving around on their two back legs all the time: they were the first dinosaurs.

Dinosaurs went on to dominate the land for 165 million years. They evolved into hundreds of different species. Ranging from about the size of a duck to 75-tonne giants, the dinosaurs inhabited tropical land environments on all continents — including Antarctica — during the Triassic, Jurassic and Cretaceous periods, 230-65 million years ago.

Naming the dinosaurs

In the early 19th century, some scientists realised that certain fossil bones they had discovered must have belonged to a group of reptiles that lived in the distant past. A new group, named *Dinosauria* ("terrible lizards"), was created for them by Richard Owen, an English anatomist, in 1842.



Brachiosaurus reaching up to the highest branches

Palaeontologists divide the dinosaurs into two major groups, based on the shape and positions of their hip bones. In "lizard-hipped" dinosaurs, or saurischians, the pubic bone of their hip sloped forwards. The saurischians were themselves divided into two major sub-groups: the meat-eating, bipedal theropods, and the plant-eating sauropodomorphs, many of which went about on four legs. "Bird-hipped" dinosaurs, or ornithischians, had a backward-sloping pubic bone. The ornithischians, all plant-eaters, were divided into several sub-groups: ornithopods, horned ceratopsians, thick-skulled pachycephalosaurians, stegosaurs and ankylosaurs.

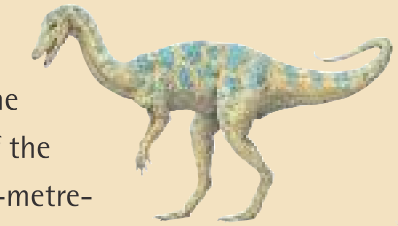
▶ *Brachiosaurus* had very sturdy hip and leg bones to support its great weight. In contrast, the vertebrae in its neck were hollow to make them as light as possible, otherwise its neck would have been too heavy for *Brachiosaurus* to lift up.

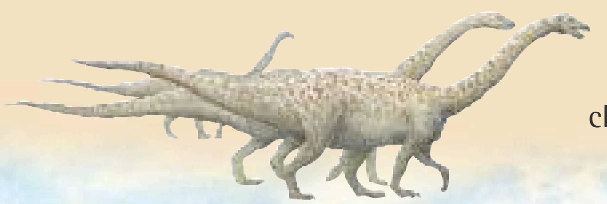
◀ *Centrosaurus* had heavy jaws and slicing teeth to cut up tough plant stems.

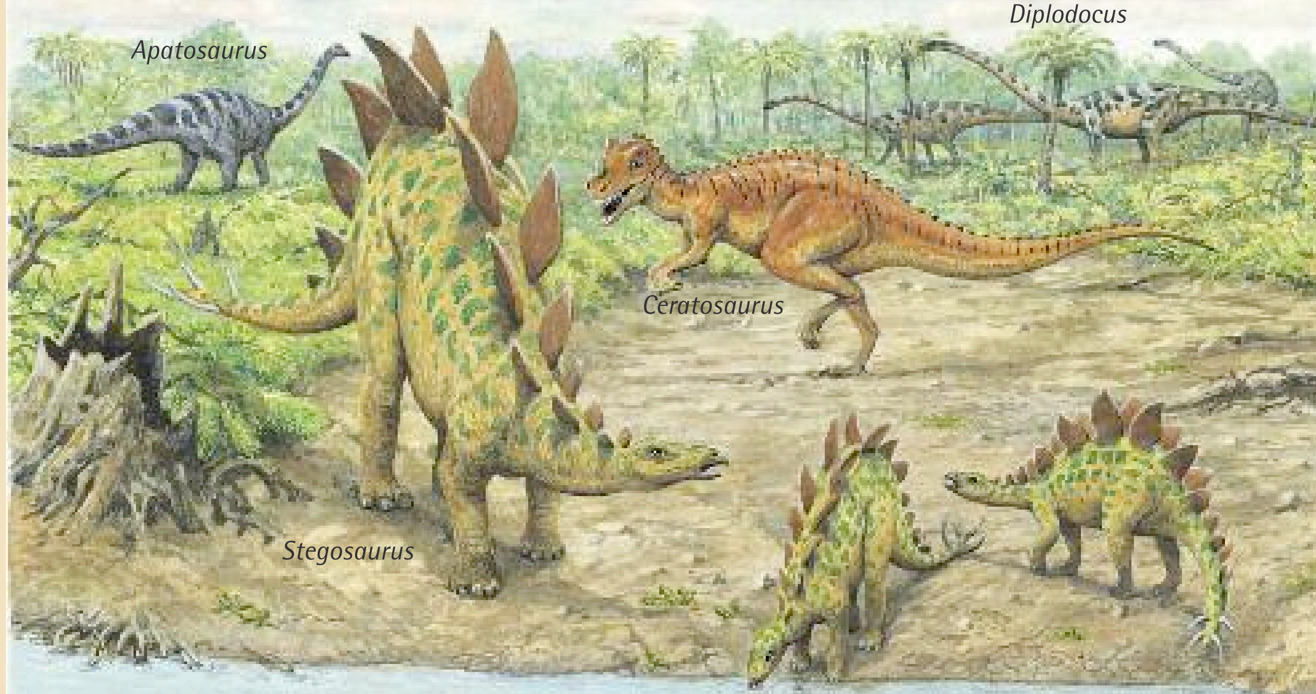
Triassic period

The first dinosaurs appeared about 230 million years ago in South America and Europe. These early dinosaurs, such as *Eoraptor (above, right)* and *Herrerasaurus (below, left)*, were small meat-eaters: theropods. They ran on legs, leaving their arms free to grasp prey.

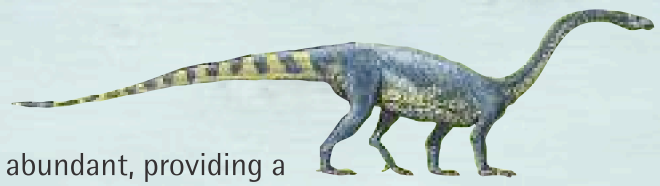
Coelophysis (below, left) was a theropod from what is now the USA. It had a long, narrow head and sharp, saw-edged teeth, which it used to devour lizards and other small prey. Large numbers of fossils have been found together, suggesting that *Coelophysis* lived in packs like wolves. The plant-eaters, or sauropods, emerged later, towards the end of the Triassic. One of the largest of the early sauropods was the 10-metre-long *Riojasaurus (below)*. Another was *Plateosaurus (bottom)*. Eight metres long, it probably spent some of its time on all fours, but normally walked and ran on its two powerful back legs. *Plateosaurus* may have used its large, curved thumb-claw to pull down branches.



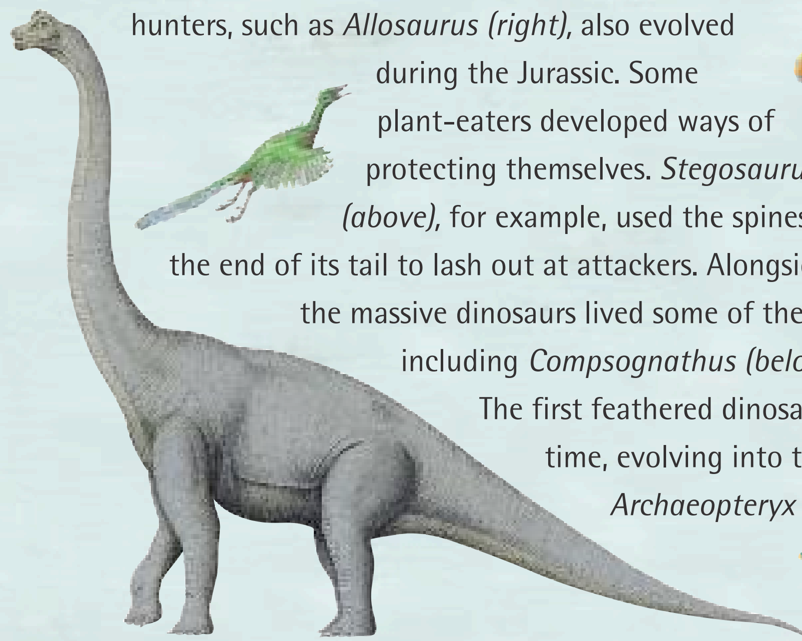




Jurassic period

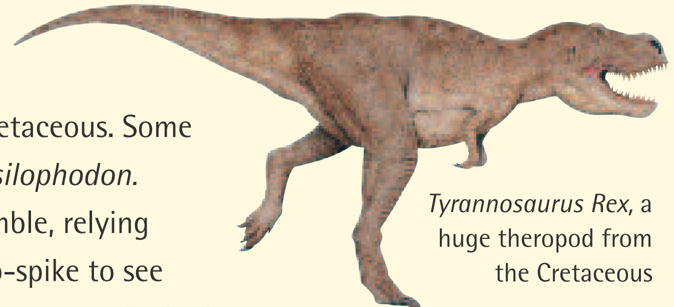


During Jurassic times the climate became wetter. Plants were more abundant, providing a rich food source for the dinosaurs. The long-necked sauropods replaced prosauropods such as *Massospondylus (above, right)* as the dominant plant-eaters, culminating in giants such as *Brachiosaurus (below, left)*. Larger, more powerful hunters, such as *Allosaurus (right)*, also evolved during the Jurassic. Some plant-eaters developed ways of protecting themselves. *Stegosaurus (above)*, for example, used the spines at the end of its tail to lash out at attackers. Alongside the massive dinosaurs lived some of the smallest known, including *Compsognathus (below, right)*, a swift predator. The first feathered dinosaurs also appeared at this time, evolving into the first birds, such as *Archaeopteryx (above, left)*.

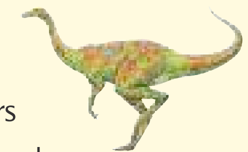


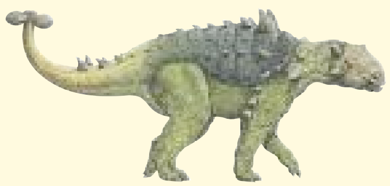
Cretaceous period

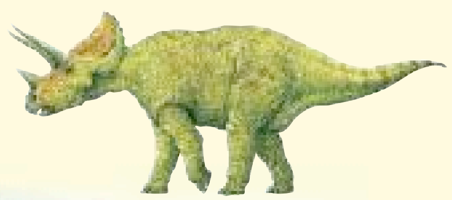
Ornithopods, able to chew their food, became more abundant during the early Cretaceous. Some were small and fast-moving like *Hypsilophodon. Iguanodon (below)* was much less nimble, relying instead on a sharp thumb-spike to see off predators. Later came the hadrosaurs, such as *Parasaurolophus (left)*, whose cheek teeth continually replaced old, worn ones. New varieties of predatory dinosaurs appeared. They included the fast-running ostrich dinosaurs, such as *Ornithomimus (right). Baryonyx (bottom)* was an unusual theropod, with a long, pointed snout like a crocodile. It waded through the shallows to eat fish. Armoured dinosaurs also evolved in the Cretaceous. Ankylosaurs, such as *Euoplocephalus (left),* were tank-like animals covered with bony plates and sides. For extra defence, they had bony clubs at the ends of their tails. For the last 20 million years of the dinosaurs' reign, ceratopsians, such as *Triceratops (right)*, were the most abundant large herbivores.

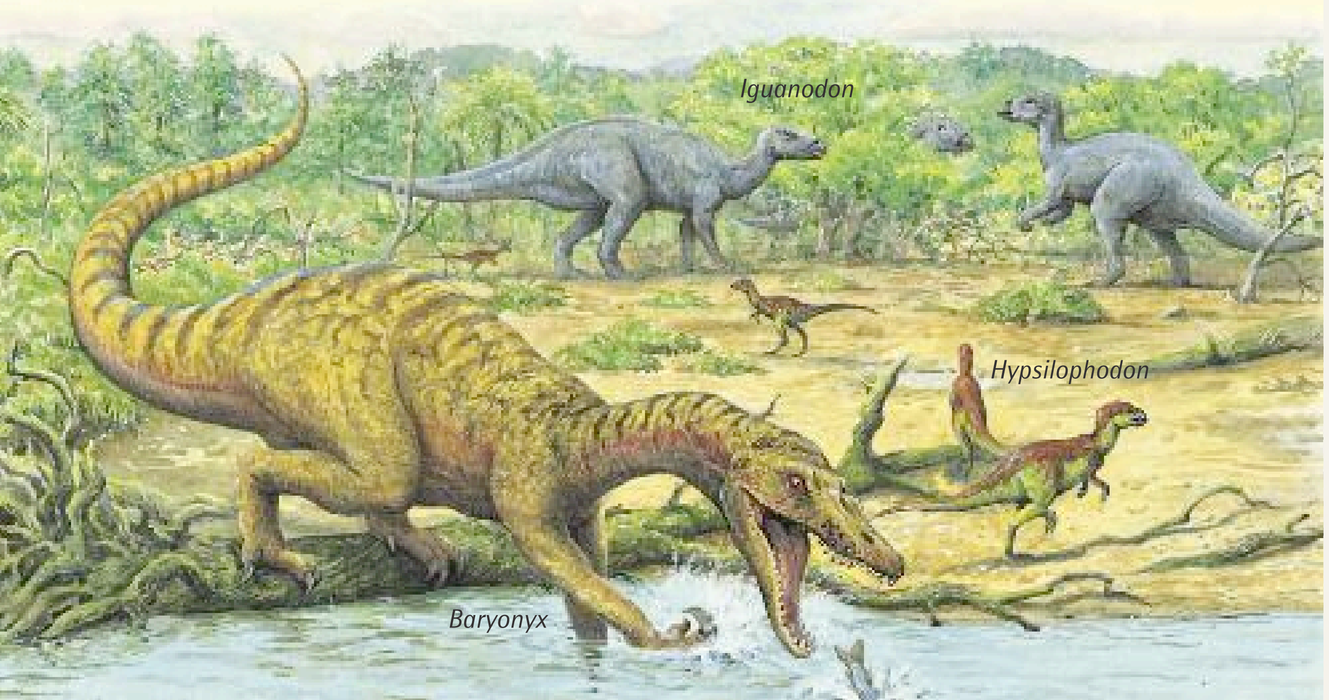


Tyrannosaurus Rex, a huge theropod from the Cretaceous









3. Tools and techniques

SO HOW DO YOU FIND a fossil dinosaur? And once it is located, how can you get it back to a laboratory without damaging it? You will need to make plans for an expedition and take the right tools with you. Even when you find a dinosaur, you should expect a long period of preparation before it is ready for scientific analysis.

The first task facing palaeontologists is to find fossils in the rocks. They concentrate their efforts on exposed rocks in certain places. Fossils are formed only in certain kinds of sedimentary rocks, those made up from sand or mud, the fragments of other rocks, or the remains of once-living organisms. Dinosaur fossils come from rocks of the Triassic, Jurassic or Cretaceous periods; there are only a few places in the world where these rocks are exposed at the surface. They include the Gobi desert, the American West and western Argentina. Geological maps, aerial photographs and satellite imagery also help to pinpoint likely fossil-bearing sites.

▼ Palaeontologists look for shapes or textures in the rock: bones or teeth have a smoother, shinier surface — or even a different colour — to the surrounding rock. Many important finds are spotted by accident.

▼ The Gobi desert of Mongolia and northern China has yielded many dinosaur fossils. In this dry terrain, the sedimentary rocks have been eroded by wind and water, which leads to fossils being newly exposed.

Excavation site

When palaeontologists find a fossil, they begin excavation by carefully chiselling and scraping away the rock, called the matrix, from around the bones. They use dental picks and other fine tools for work on especially tiny, delicate fossils. The matrix is not normally completely removed from around a fossil until it reaches the laboratory. Extracting a specimen from the rock and removing the rock that lies above it, the overburden, can be difficult, and risks damaging the fossil. Throughout the excavation, scientists take photos and make notes about the fossil's exact location.

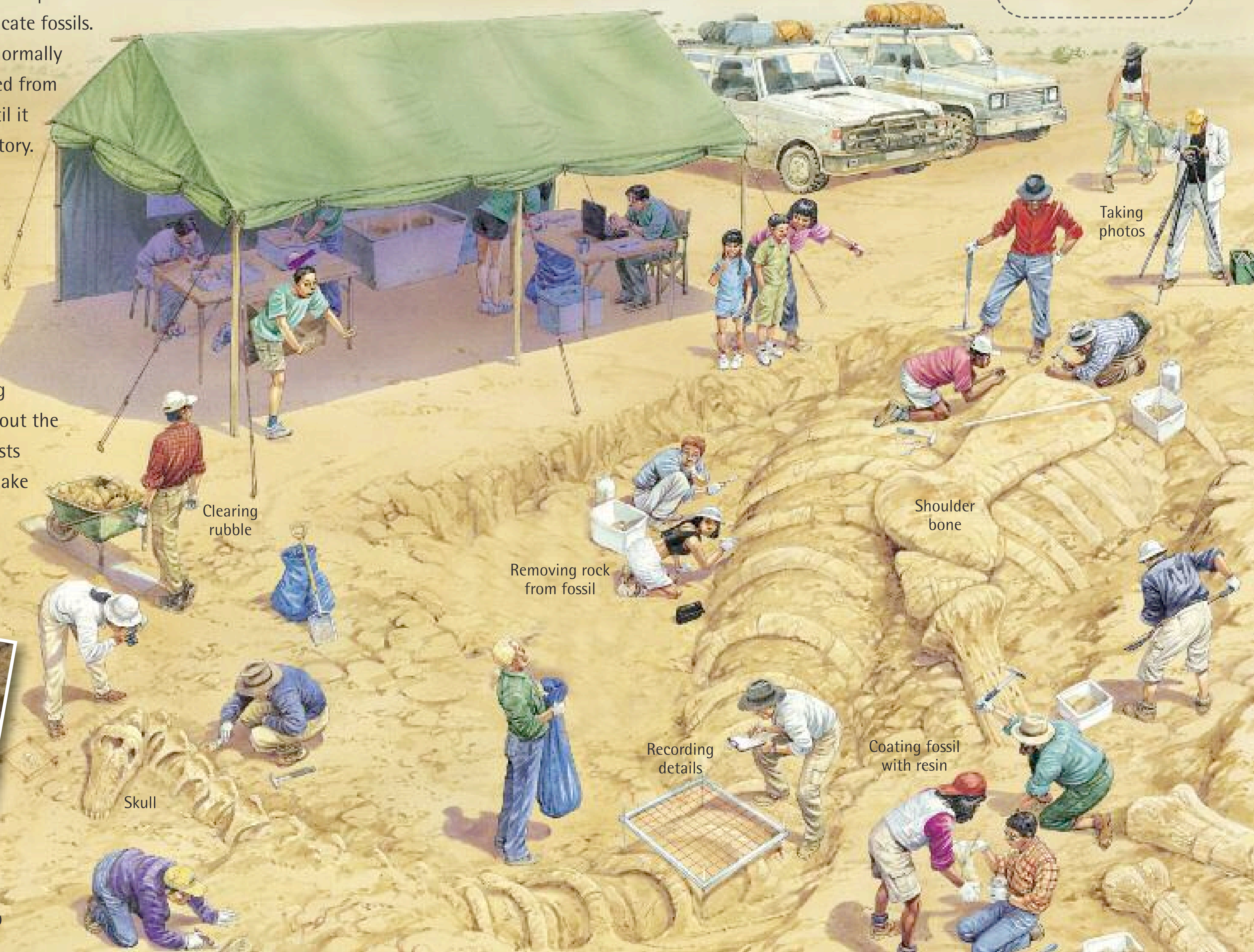
Most palaeontologists create detailed site maps showing the location and orientation of every bone in its original place. Finding other animal and plant fossils nearby will help to reveal more about the ancient environment and possibly what the dinosaur fed on.

Moving the fossil

Before the block containing the fossil is freed from the ground, the palaeontologists coat the bones with glue or resin to prevent them from crumbling. Next, they wrap the surface of the fossils in bandages soaked in plaster of Paris – as if putting a broken arm in a cast. The fossil is now stabilized: it will be kept together and protected from damage during transport. The block is dug out and its underside stabilized. The fossil is now ready for transport back to the laboratory.

GPS

Palaeontologists often work in remote locations. They can use a Global Positioning System (GPS) to record their exact location.



▼ Tools used by an excavation team include shovels, hammers, sieves and brushes, as well as a range of hammers, chisels, picks and scalpels.

Making casts

After cleaning and repairing the bones, preparators make exact copies of them. This is to make scientific study easier and to enable reassembling a skeleton for display. Rubber moulds of the bones are filled with liquid plastic that solidifies into exact copies. The tiniest details are preserved in the casts. Missing bones need to be made, either by recreating bones from similar dinosaur fossils, or by producing new ones using computer generated modelling techniques.

▲ This *T. rex* skull was copied twice. The first, the research cast, is a replica of the original skull, exactly as it was found with its snout squashed — damage that occurred shortly after death. This cast allows scientists to study it with all the original details. The second copy was pieced back together to create a corrected cast: a reconstruction of what the head would have looked like in life.

Dinosaur lab

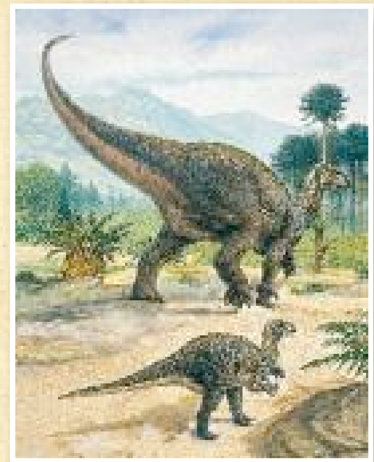
Once the blocks containing the precious fossil bones arrive at the laboratory, work begins on removing the rest of the matrix *(bottom)*. First, the preparators clear away large pieces of rocky matrix by using a hammer and chisel or a miniature jackhammer, a kind of pneumatic drill. For particularly thick lumps of matrix, a shot-blaster, which fires iron or plastic pellets at the rock, might be used. As each part of the fossil is exposed, the surface is coated with liquid rubber to protect it from the full force of the pellets. If the matrix is made of limestone it might be dissolved away with acid. Although slow, this technique is good for small, delicate fossils, so long as it does not damage them.

Next, the bones are cleaned of all remaining grains of rock using a miniature sandblaster, a dentist's drill *(above)* or other tools, including scalpels and needles. This is painstaking work: it can take years to prepare a whole skeleton.

4. Dinosaur studies

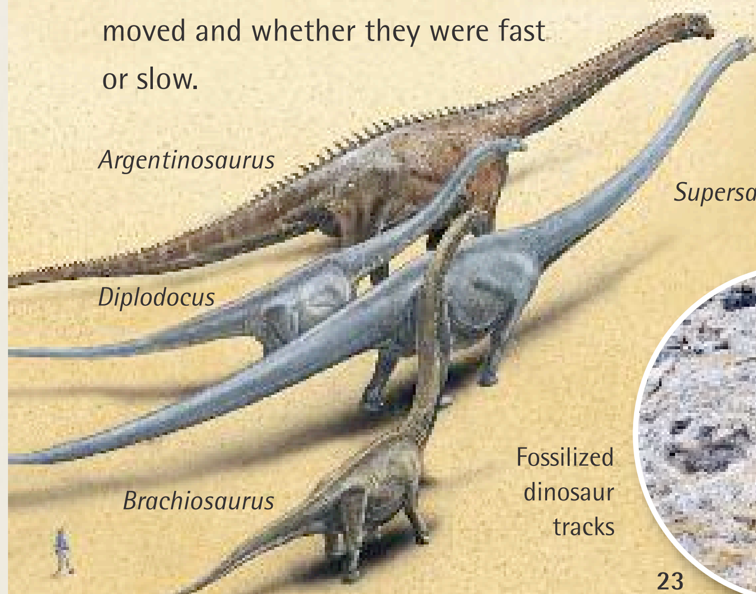
◀▲ The long bones in its back legs show *Iguanodon* walked bipedally. The hooves on the ends of its fingers tell us that it must have walked on all fours as well. Infants, which had proportionally shorter arms, probably spent more time running on two legs.

YOU HAVE found your fossil dinosaur, excavated it, brought it back to your laboratory and now have a chance to study it in detail. So what can you learn about it? The bones themselves can reveal a surprising amount of detailed information. Once you consider the biology and lifestyle of modern animals, a picture of how animals lived millions of years ago starts to emerge.



So how can we work out how different dinosaurs walked and ran? Study of fossil skeletons reveal the dinosaur's body type: whether it was light-boned and bipedal, or a heavy-boned quadruped. Fossilized tracks indicate how a dinosaur stood, how fast it was going and whether it travelled alone or in groups. Biomechanics, applying the principles of engineering to animals, tells us how they may have moved and whether they were fast or slow.

▼ The similarity in build between *Ornithomimus* and an ostrich tells us that they probably sprinted at similar speeds: 70 km/h.



Fossilized dinosaur tracks

◀ From study of fossil tracks, we know that sauropods walked on tiptoe. As in elephants, a wedge of tissue under their heels lifted them off the ground to make walking easier. The absence of tail-drag marks reveals that sauropods must have walked with their tails up, balanced by their long necks.

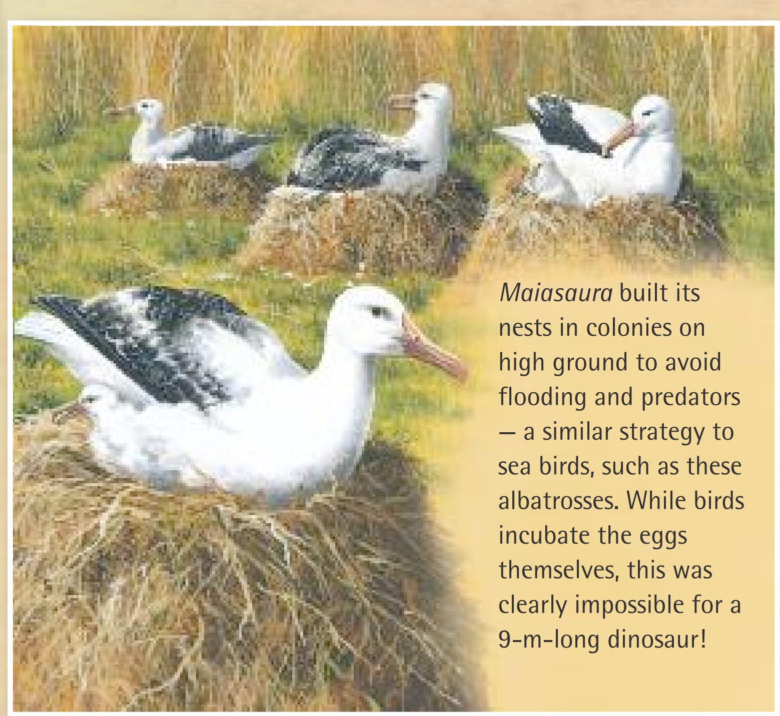
Raising their young

The discovery of fossilized dinosaur eggs, the nests that they were hatched in and even the baby dinosaurs inside the eggs, gives palaeontologists a great deal of information about how dinosaurs brought up their young. Taken together with the study of nesting habits in modern birds and reptiles, this helps us to build up a picture of the dinosaurs' parenting behaviour.

Close examination of a fossilized nesting colony belonging to the hadrosaur *Maiasaura* tells us both about how the nests were constructed and the early years of the hatchlings. The nests were packed together like those of modern seabirds with the gap between them just sufficient to allow the parents to visit their nests without disturbing their neighbours. The nests were mounds of soil. The eggs were incubated by heat coming from rotting vegetation piled on top of them, rather than a parent sitting on the nest.

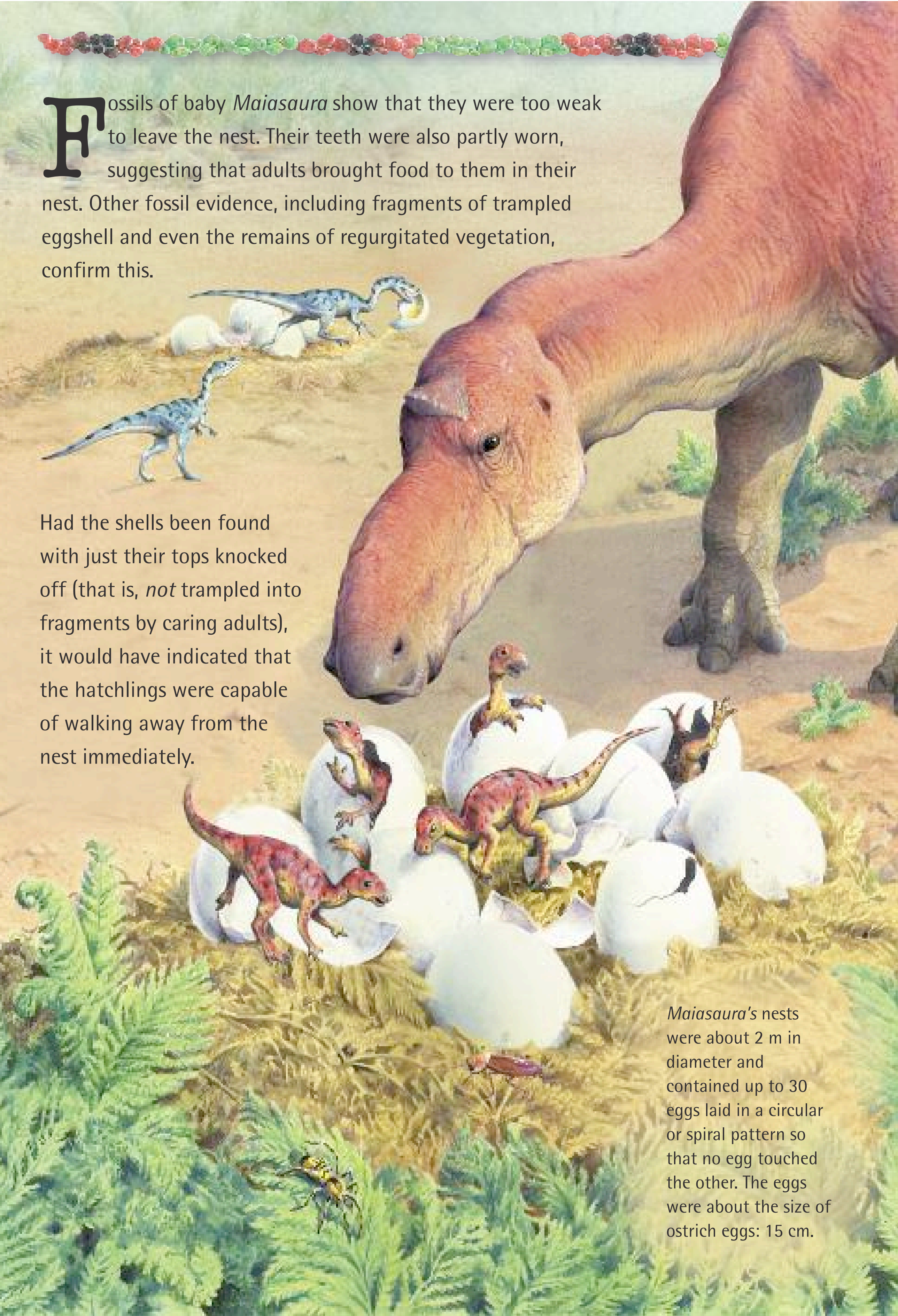
▲ The study of fossilized dinosaur eggs shows they had shells thin enough to allow oxygen to pass through, and for the baby to break out. The textured surface would have prevented the tiny pores in the shells from being blocked.

▲ There are a few rare examples of fossilized eggs with the embryonic dinosaur still inside. The baby's "cute" appearance (large head and eyes) would have made a mother *Maiasaura* feel maternal towards her brood, just like other animal mothers today.



Maiasaura built its nests in colonies on high ground to avoid flooding and predators – a similar strategy to sea birds, such as these albatrosses. While birds incubate the eggs themselves, this was clearly impossible for a 9-m-long dinosaur!

Fossils of baby *Maiasaura* show that they were too weak to leave the nest. Their teeth were also partly worn, suggesting that adults brought food to them in their nest. Other fossil evidence, including fragments of trampled eggshell and even the remains of regurgitated vegetation, confirm this.



Had the shells been found with just their tops knocked off (that is, *not* trampled into fragments by caring adults), it would have indicated that the hatchlings were capable of walking away from the nest immediately.

Maiasaura's nests were about 2 m in diameter and contained up to 30 eggs laid in a circular or spiral pattern so that no egg touched the other. The eggs were about the size of ostrich eggs: 15 cm.

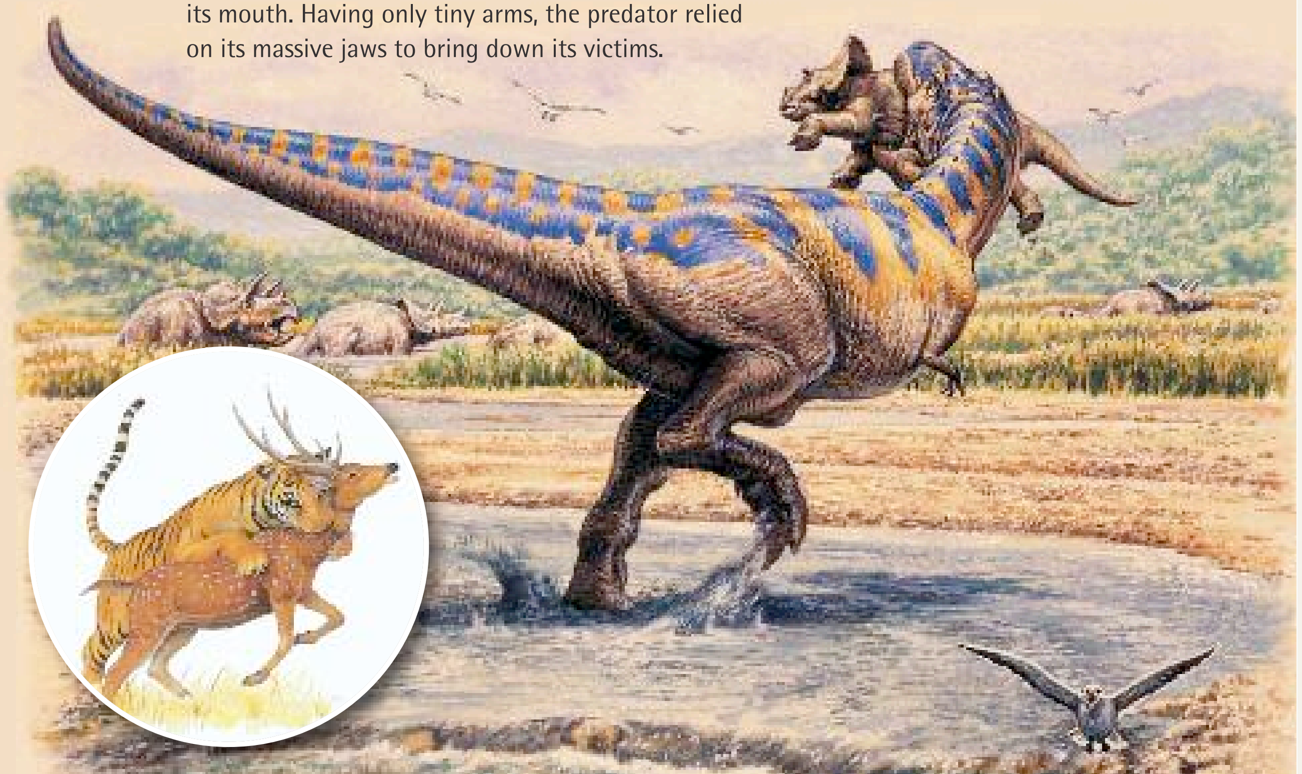
▲ A fossil of *Velociraptor* and *Protoceratops* locked in combat provides direct evidence of a dinosaur attack. The animals were buried in sand, perhaps during a storm. One of *Velociraptor's* curved claws is embedded in its prey's neck. It probably tried to pierce the organs in *Protoceratops's* throat.

Attack ...

The fossil record shows that meat-eating dinosaurs included not only giant predators such as *Allosaurus* and *Tyrannosaurus rex*, but also a wide range of smaller hunters. From the study of their bones and those of other dinosaurs close by, and by applying our knowledge of how modern animals hunt, we can re-create the hunting strategy of predatory dinosaurs.

From the evidence of trackways, we know that some (but not all) big predators hunted alone. The method of attack was probably similar to that of a modern tiger *(bottom, left)*. Having spotted an old, young or disabled individual in a herd, the predator would bide its time watching and waiting, while staying out of sight. Seeing its quarry straying from the herd, it broke cover and rushed at it, plunging its teeth into its body. The sharp, saw-edged teeth sliced through the flesh.

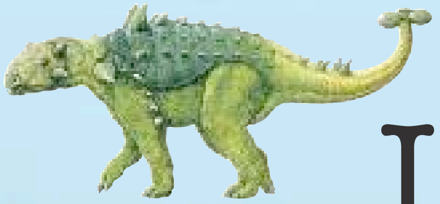
▼ A *Tyrannosaurus rex* seizes a young *Triceratops* in its mouth. Having only tiny arms, the predator relied on its massive jaws to bring down its victims.



The discovery of the remains of several *Deinonychus* lying near the body of the much larger herbivore, *Tenontosaurus*, suggests that the predators may have hunted in packs. Swift and agile, *Deinonychus* had a relatively large brain, and may have used its intelligence to launch a co-ordinated attack. Hidden in vegetation near their prey, the group gradually surrounded it, closing off all escape routes. At the right moment, they leapt on to their victim, using their sickle-shaped claws to stab through its thick skin. We cannot be certain about this event, however. Another interpretation of the fossil find is that several of the predators fought each other over a carcass they were scavenging.

▲ From studying the skull of *Troodon*, we can tell it had a large braincase and big, forward-facing eyes. This small, speedy predator may have hunted at night, making good use of its sharp, stereo vision.

▶ The way a modern pack-hunter, the lion, hunts its prey shows how *Deinonychus* could have gone about its task. Several lionesses stalk a wildebeest, encircling their chosen victim. They catch it with a rush and a leap.



▲ *Euoplocephalus's* fossil remains show that its back and head, and even its eyelids, were all covered by bony plates. Only its belly was soft, forcing an attacker to try and flip this 2-ton dinosaur on to its back. This was no easy task, especially since *Euoplocephalus* also carried a huge bony club on the end of its tail. Its ribs and hips were fused together to provide an anchor for the massive muscles in its tail.

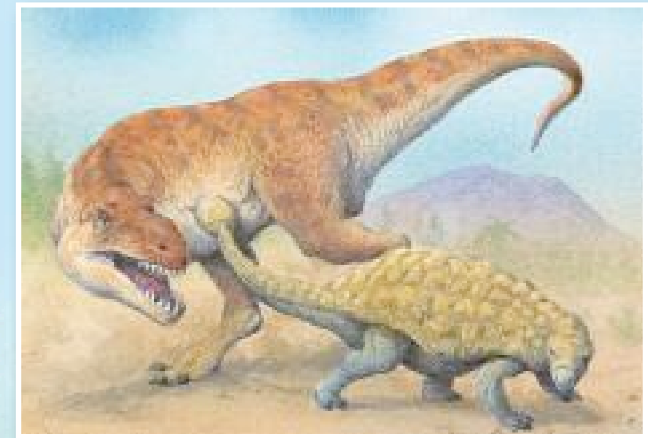
… and defence

Like modern herbivores, dinosaurs had various ways of defending themselves. These included: being very large, herding together, running away, camouflage and defensive armour, as well the active use of teeth, claws, horns and spikes as weapons.

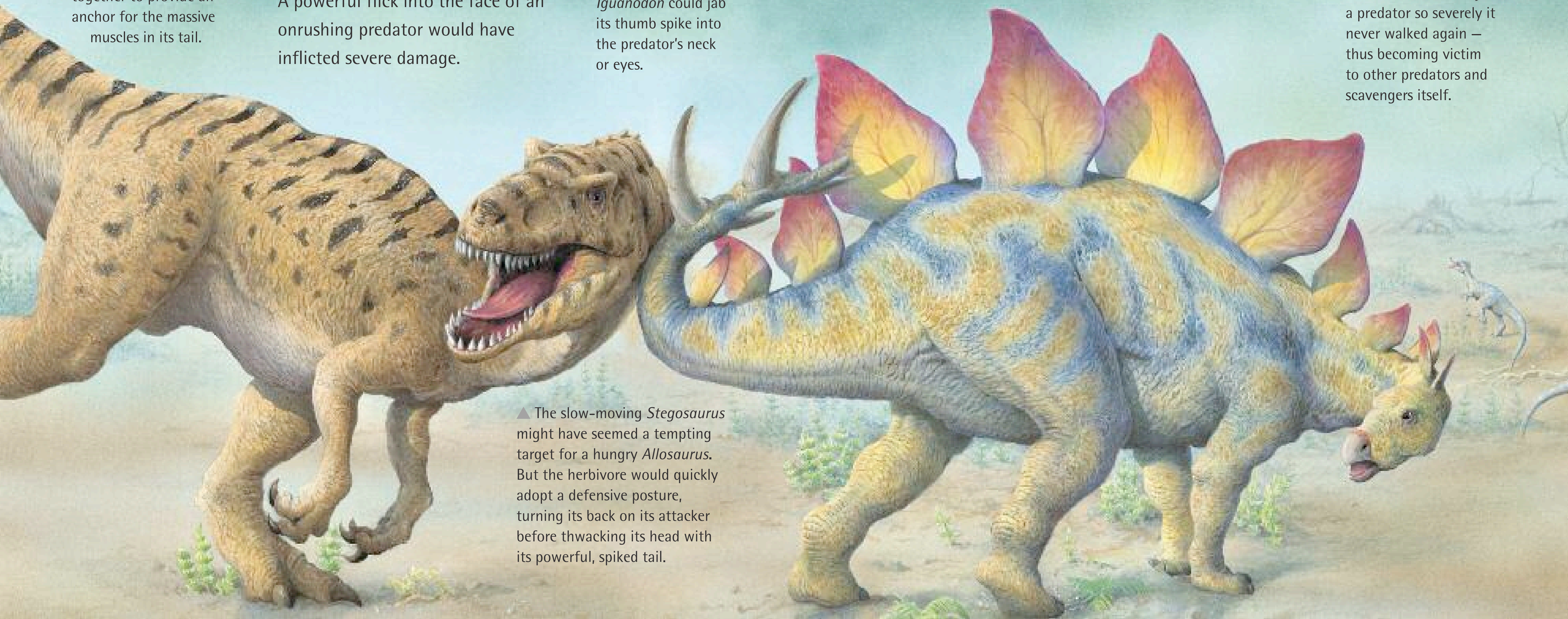
Stegosaurus carried a lethal defensive weapon: its fossil remains include a set of four long spikes sticking out from the its tail. A powerful flick into the face of an onrushing predator would have inflicted severe damage.

▲ If attacked, *Iguanodon* could jab its thumb spike into the predator's neck or eyes.

Studies of *Stegosaurus's* bone structure confirm how the weapon could be used. Unlike many other dinosaurs, the tendons (straps of muscle) in its tail had not turned to bone. This meant that the tail remained flexible: it could swish from side to side. Its powerful, short forelimbs allowed it to swivel round quickly and launch its attack. Many of the fossil tail spikes found show damage, suggesting they were used in combat. Palaeontologists have even found a punctured tail bone belonging to an *Allosaurus* into which a tail spike fits snugly.



▲ *Talarurus*, like *Euoplocephalus*, was an ankylosaur. Here it is repelling an attack by *Tarbosaurus*, a giant predator. One blow from the tail club could injure a predator so severely it never walked again — thus becoming victim to other predators and scavengers itself.



▲ The slow-moving *Stegosaurus* might have seemed a tempting target for a hungry *Allosaurus*. But the herbivore would quickly adopt a defensive posture, turning its back on its attacker before thwacking its head with its powerful, spiked tail.

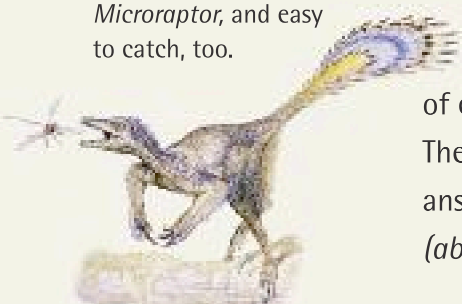
Dinosaur diets

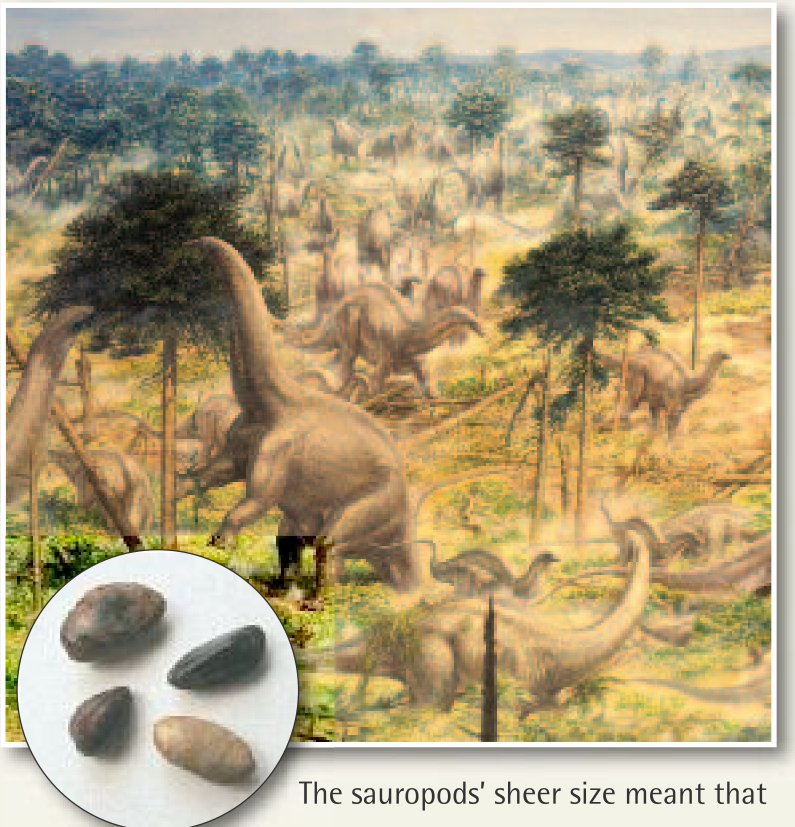
Dinosaurs can be divided into plant-eaters or meat-eaters. The shape of a dinosaur's jaws or teeth reveals to which group it belonged and how it obtained its food. We know from the fossil record what food was available at a certain time. In some fossils, the stomach contents have also been preserved, providing vital clues about diet. We can also work out how dinosaurs fed simply by studying modern animals' eating habits.

▲ *Saurolophus*, a hadrosaur, had a flat beak and hundreds of tough cheek teeth. Using its beak, it tore off vegetation. Its cheek teeth allowed it to feed on the toughest plant material: bark, pine cones and conifer needles – food no other plant-eater could digest.

▼ Horned dinosaurs, such as *Triceratops*, used their narrow beaks to slice off shoots and leaves, which their scissor-like teeth then chopped up.

▼ As with birds, insects would have been a nutritional food for tiny dinosaurs, such as this *Microraptor*, and easy to catch, too.





The sauropods' sheer size meant that they would have needed huge amounts of food in the form of plant matter to nourish them. Yet their teeth were small, few in number and incapable of chewing. How could they digest their colossal meals? The presence of pebbles in some fossil remains provides the answer. Known as gastroliths, these polished, rounded pebbles *(above, inset)* were a vital part of the digestive system.

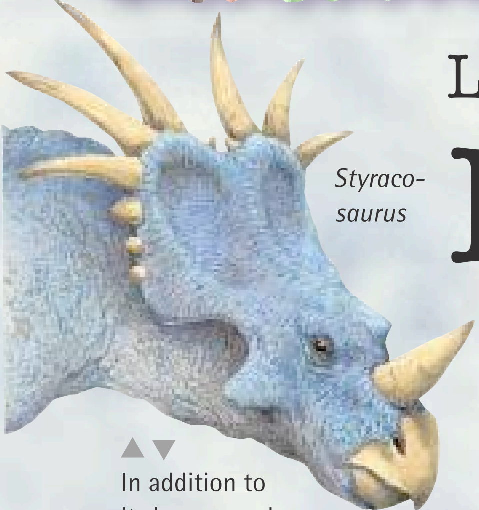
From study of how birds – the dinosaurs' closest modern relatives – eat, we know that they swallow grit or small stones to fill their gizzard, a part of their stomach. Muscular movements inside the gizzard cause the stones to grind the food into a paste, which can then be digested in the intestines. Sauropods such as *Apatosaurus (opposite, centre)* could digest their vast daily intake of unchewed vegetation with the help of gastroliths in the same way.

▼ *Compsognathus* was a tiny predator, 30 cm tall . The remains of a lizard, *Bavarisaurus*, were discovered inside its ribs.

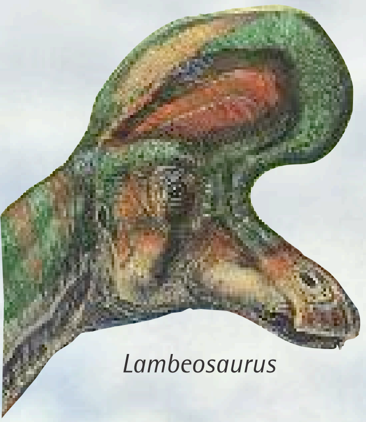
For meat-eating dinosaurs, their food had to be found or caught. From the behaviour of modern lions and hyenas, we know that few large meat-eaters would turn down the opportunity to scavenge, or steal the kill of others. It is likely, however, that large theropods, with their powerful build, were primarily active hunters of other dinosaurs. We know from fossil evidence of stomach contents that some predators, especially smaller ones (much commoner in the fossil record than the giants) fed on smaller animals, such as fish, lizards, mammals and insects. Studies of fossilized dung show that predators were very inefficient feeders: food passed quickly through them without being fully digested.

▼ Fish scales have been found inside the remains of *Baryonyx* but it is likely that it hunted other prey as well. No large land animals can survive on a diet of fish alone. *Iguanodon* bones have also been found inside *Baryonyx's* body cavity, suggesting that it could have scavenged on its corpse.

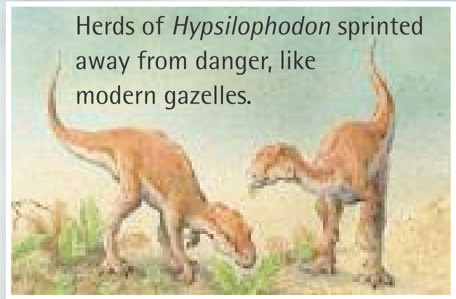
Living in a herd



▲▼ In addition to its large nose horn, *Styracosaurus* had a large neck frill with six long spikes. As with *Lambeosaurus's* large and possibly colourful crest, these features were used by males in courtship displays.



From the evidence of "mass graves", fossilized remains of hundreds of individuals found close together, we know that a number of plant-eating dinosaur species lived together in herds. Many modern herbivores live like this, too. So palaeontologists' insight into how herding dinosaurs behaved can be helped by studying the behaviour of modern herding animals.

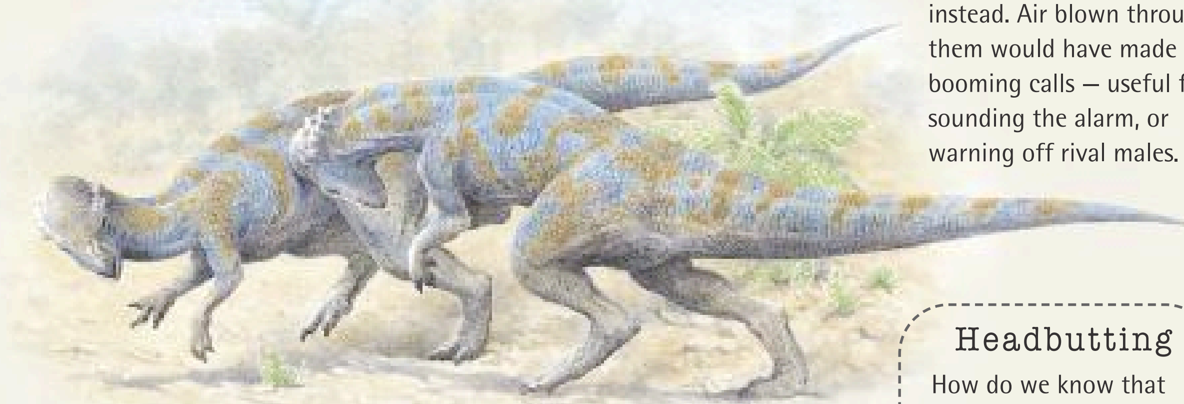

Herds of *Hypsilophodon* sprinted away from danger, like modern gazelles.

Modern herding animals – for example, those from the African savannah grasslands – live together for protection from predators, and as the safest way in which to bring up their young. The approach of a predator would be more likely to be spotted. And the predator would probably be deterred from attacking a group of stampeding adult dinosaurs, preferring to seek out a sick, elderly or juvenile individual.

▼ A herd of *Mamenchisaurus* migrate to lusher feeding grounds, just as wildebeest and other herding animals do today. The juveniles walk in the centre of the group, for protection from predators.

Many herding dinosaur species had head crests (hadrosaurs) or a neck frill and an array of horns (ceratopsians). In both cases, these features had several uses. The shape and colours may have allowed members of the same family group to recognize one another, just as today's antelopes do from the shape of their horns. Because the sizes of the crests and horns vary a lot, we can deduce that they were larger in males than females, common in modern animals. It is therefore likely that males deliberately paraded their crests, horns or neck frills in an attempt to win the attentions of females during mating season. Male peacocks are an example of modern animals that demonstrate this pattern of behaviour, known as "sexual display".

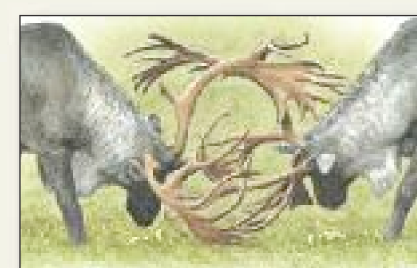

▲ *Parasaurolophus* had a long, backwards-curving, bony crest. Hollow tubes inside it were linked to its nasal passages. Lacking vocal chords, dinosaurs could not make vocal sounds, but perhaps the tubes produced noises instead. Air blown through them would have made booming calls – useful for sounding the alarm, or warning off rival males.



Besides showing off their crests or horns, male dinosaurs competed for females in other ways. Like many animals today, they fought each other for dominance. Male reindeers compete by pushing each other with their antlers *(right)*. Dinosaurs probably fought in a similar way. We know from fossil evidence that the horns of *Triceratops*, for example, were not sturdy enough to defend it from large predators. But they could have been used in sparring contests with others of its kind. The thick, domed skull of *Pachycephalosaurus* *(above)* may have been used for butting contests, just as billy goats do today. This might have resulted in serious injuries, so it is more likely that they butted each others' flanks instead.

Headbutting

How do we know that *Pachycephalosaurus* did not engage in head-butting? Its skull was not tough enough to withstand the impact of a head-on collision. There is also no evidence of damage on fossil skulls.



▼▶ Studies of the fossils *(below)* of the dinosaur *Caudipteryx (right)* show that it had fans of feathers on its hands and tail. Its body was covered in short, down-like feathers.

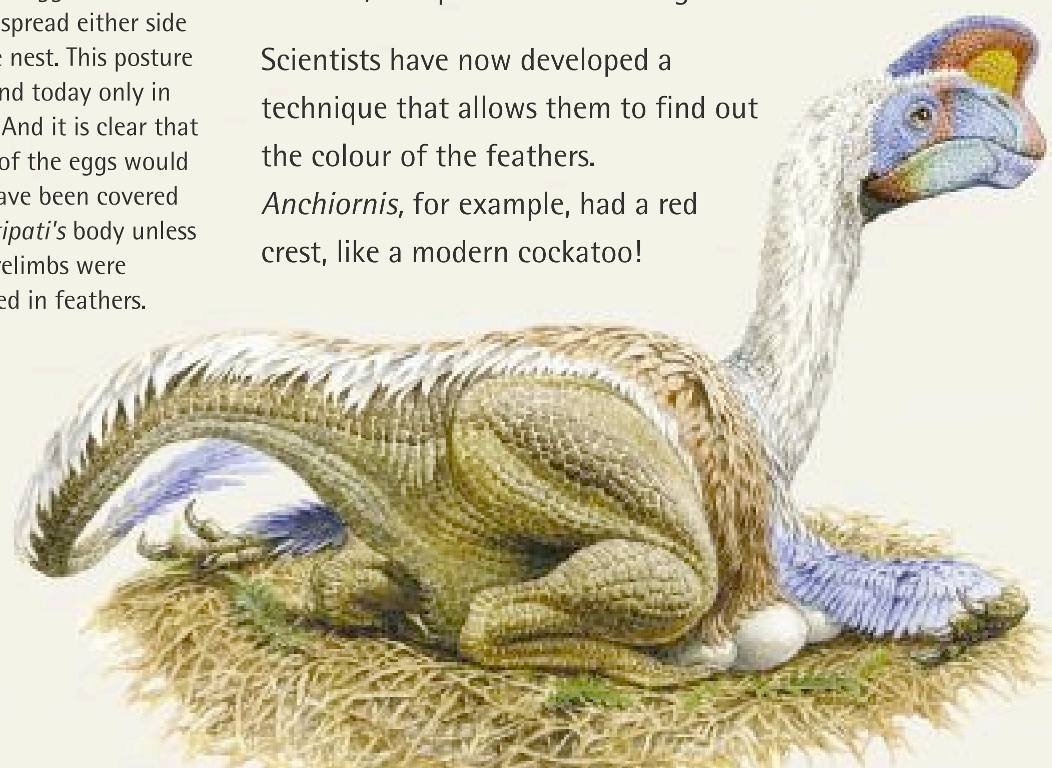
Feathers

How do we know that some dinosaurs did not have the scaly skins of today's reptiles, but coats of feathers instead – much more like their only living descendants, the birds?

Fossils of the Jurassic bird, *Archaeopteryx*, known from skeletal similarities to be closely related to small theropods, clearly show well-preserved feathers. The first dinosaur fossils that had feather impressions were discovered preserved in fine-grained volcanic ash in Liaoning province, China, in the 1990s. Even where feather impressions are absent, the existence of quill knobs in the arm and leg bones shows that feathers must have been present. The presence of a pygostyle, the fused bones at the tip of the tail which support tail feathers, also provides convincing evidence.

▼ Evidence for feathers can also come from what we know about dinosaur behaviour. Fossils of *Citipati* have been found in brooding positions. The most famous of these is known as "Big Mamma". They are sitting on top of their eggs, with their limbs spread either side of the nest. This posture is found today only in birds. And it is clear that most of the eggs would not have been covered by *Citipati's* body unless its forelimbs were covered in feathers.

Scientists have now developed a technique that allows them to find out the colour of the feathers. *Anchiornis*, for example, had a red crest, like a modern cockatoo!



◀ Sue's skeleton is mounted for public display at the Field Museum of Natural History in Chicago. A special steel frame "cradles" her bones. Her real skull, which is too heavy for the mounted skeleton, is displayed in a separate case.

5. Project T.Rex

THE LARGEST AND best preserved specimen of *Tyrannosaurus rex* ever found was discovered in 1990 at the Cheyenne River Indian Reservation, in western South Dakota, USA. It (we don't know whether it was male or female) was named "Sue" after Sue Hendrickson, the palaeontologist who found the fossil bones. Sue was 80% complete. Scientists believe she was covered by water and mud soon after death: this prevented scavenging animals from carrying away the bones.

▲ Sue's 60 saw-edged teeth, some more than 25 cm long, were perfect for biting through flesh and bone. Each tooth was thick enough to allow Sue to crush bone without them snapping. The teeth replaced themselves every two to three years.

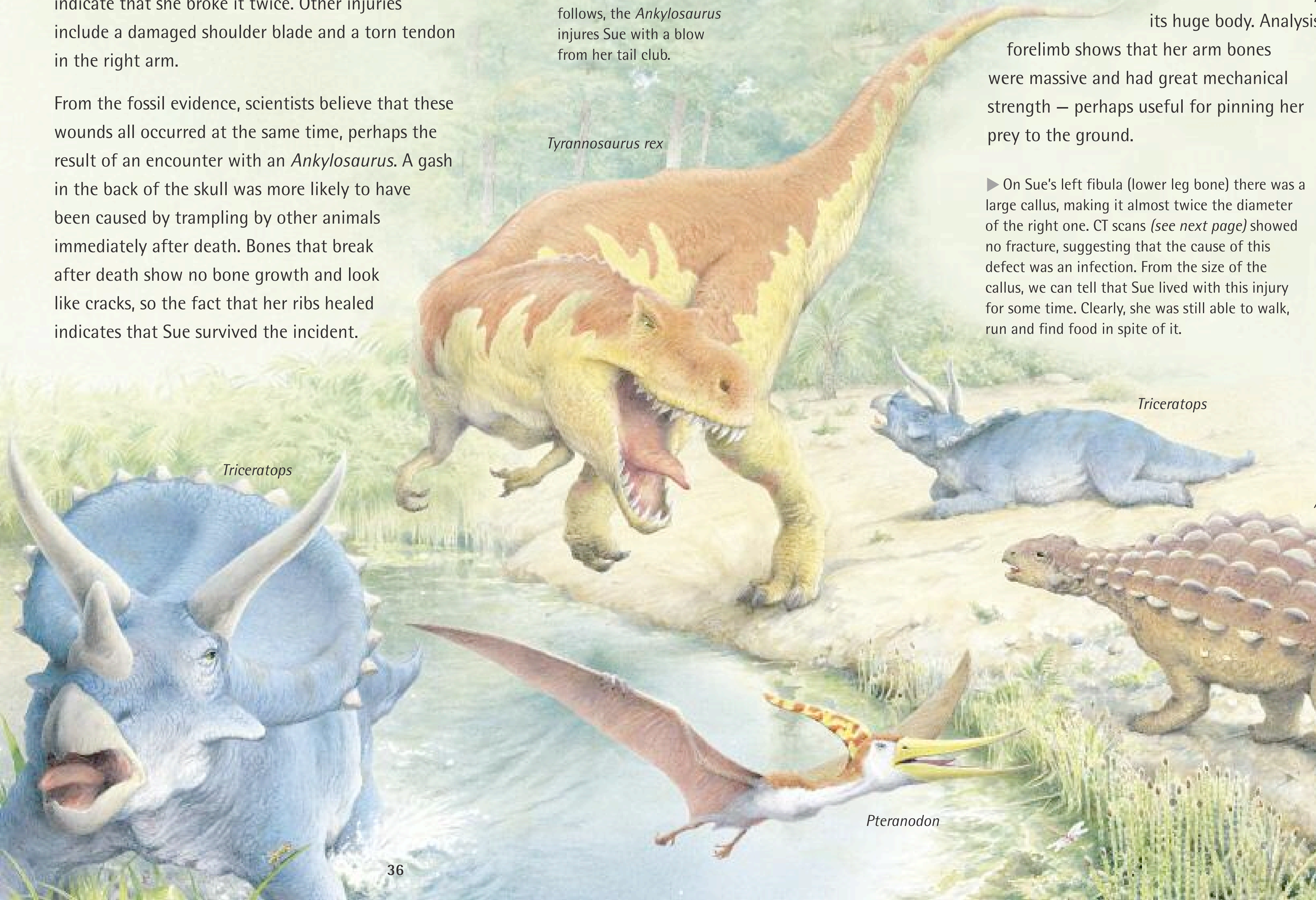
Examination of Sue's skull revealed rows of holes above and below her teeth that once held nerves and blood vessels. At first, scientists thought the holes in Sue's lower jaw were where another dinosaur had bitten her. But the spacing of the holes do not resemble bite marks and the edges of the holes are smooth rather than jagged, so it is more likely that they were caused by an infection. This may have killed Sue outright, or may have made it so painful to swallow that she died of starvation. As in other predators, Sue's eye sockets faced forward, meaning that, like humans, she had good 3D vision.

The life of Sue

Studies of her bones reveals that, during her lifetime, Sue suffered several broken ribs. Evidence from bumps on one of her ribs indicate that she broke it twice. Other injuries include a damaged shoulder blade and a torn tendon in the right arm.

From the fossil evidence, scientists believe that these wounds all occurred at the same time, perhaps the result of an encounter with an *Ankylosaurus*. A gash in the back of the skull was more likely to have been caused by trampling by other animals immediately after death. Bones that break after death show no bone growth and look like cracks, so the fact that her ribs healed indicates that Sue survived the incident.

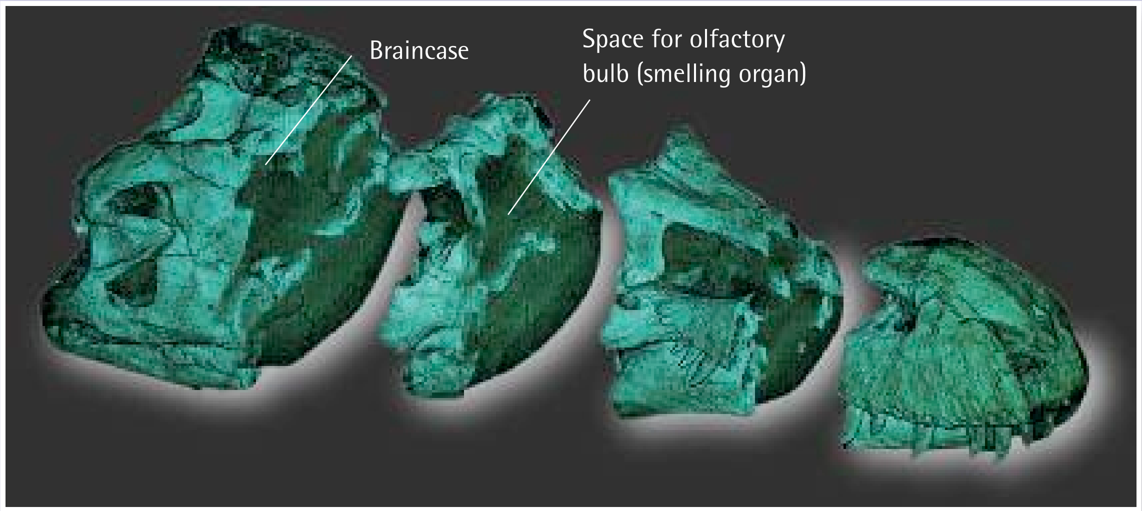
▼ In this imaginary scene, Sue, the *T. rex*, is about to kill an injured *Triceratops* when an *Ankylosaurus* challenges her. In the contest that follows, the *Ankylosaurus* injures Sue with a blow from her tail club.



From studying slices of Sue's bones under a microscope to count the rings – like tree trunks, dinosaur bones grow by a layer each year – we can tell that Sue was 28 when she died: near the upper limit of her natural life-span, scientists believe.

T. rex's arms were tiny compared to the rest of its huge body. Analysis of Sue's near-complete forelimb shows that her arm bones were massive and had great mechanical strength – perhaps useful for pinning her prey to the ground.

▶ On Sue's left fibula (lower leg bone) there was a large callus, making it almost twice the diameter of the right one. CT scans *(see next page)* showed no fracture, suggesting that the cause of this defect was an infection. From the size of the callus, we can tell that Sue lived with this injury for some time. Clearly, she was still able to walk, run and find food in spite of it.



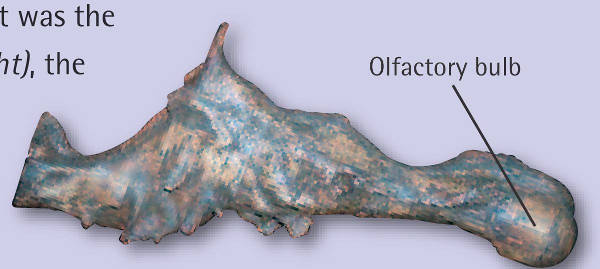
This is a digitally generated image of Sue's skull, produced by computed tomography (CT) scanners. This technique, using powerful x-rays to create detailed images in slices, allowed palaeontologists to examine the inside of Sue's head without damaging it. CT scans are usually used for imaging the insides of people in hospitals.

Bird-brained

CT scans revealed some details of brain anatomy that *T. rex* shared with birds: the layout of the brain and the branching pattern of some of the nerves inside the head. This evidence suggests that it was quite closely related to modern birds.

Brain and senses

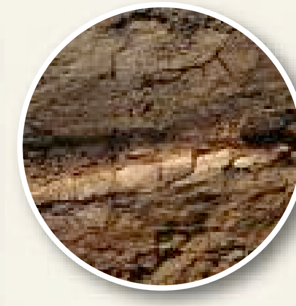
The soft parts inside Sue's head did not fossilize, but there is still a large amount of information that can be gained from studying the spaces left inside her skull – for example, her brain cavity. The CT scans *(above)* show that her brain was 30.5 cm long and shaped like a knobbly sweet potato. One of the largest regions of it was the olfactory bulb *(right)*, the part used for smelling.



The scans also reveal an unusually large tube running between the nose and the brain. This is the olfactory passage, where the nerves for smelling pass through. It is even larger than the hole at the rear of the skull where the spinal cord –the bundle of nerves that runs to the rest of the body – links to the brain. We can tell from this that Sue had an extremely strong sense of smell, vital for an animal that sniffs out prey or scavenges for food.

6. Solve a mystery

FOR MORE THAN 160 million years, the dinosaurs ruled the land unchallenged. Then, quite suddenly, about 65 million years ago, they were gone. There are no more fossils of dinosaurs after this time, the end of the Cretaceous. But what disaster killed the dinosaurs?



In North America the K-T boundary rocks consist of a layer of clay, probably debris from the impact, and containing glass spherules. Just above this is a layer of iridium with fragments of shocked quartz.

In 1980, a team led by physicist Luis Alvarez discovered that layers found all over the world at the boundary between the Cretaceous and Tertiary rocks, called the K-T boundary (K for *Kreidezeit*, German for Cretaceous; T for Tertiary) contain a concentration of the metal iridium many times greater than normal. Iridium is very rare in the Earth's crust, but known to be abundant in most asteroids. So Alvarez suggested that an asteroid may have struck Earth at the time of the K–T boundary.

Further evidence was the abundance of spherules (tiny glass spheres) and shocked quartz in the K-T boundary rocks. The glass is formed when rocks are melted, blasted into the air as droplets and immediately frozen – the exact sequence of events that might follow an asteroid impact. Shocked quartz occurs only when rocks have been struck by a massive force, such as that found at asteroid sites.

The search was on for the crater where the asteroid landed 65 million years ago. In 1990, part of the buried remains of an asteroid impact crater were identified in the Yucatán Peninsula, Mexico *(above)*. It is now generally accepted that the Chicxulub crater is the impact site for the K-T asteroid that smashed into Earth, wiping out the dinosaurs.

Fern evidence

Just above the K-T boundary, the fossil record shows a sudden increase in fern spores, indicating a rapid recolonization by ferns. These are the first plants to grow in a devastated environment, such as after a volcanic eruption.

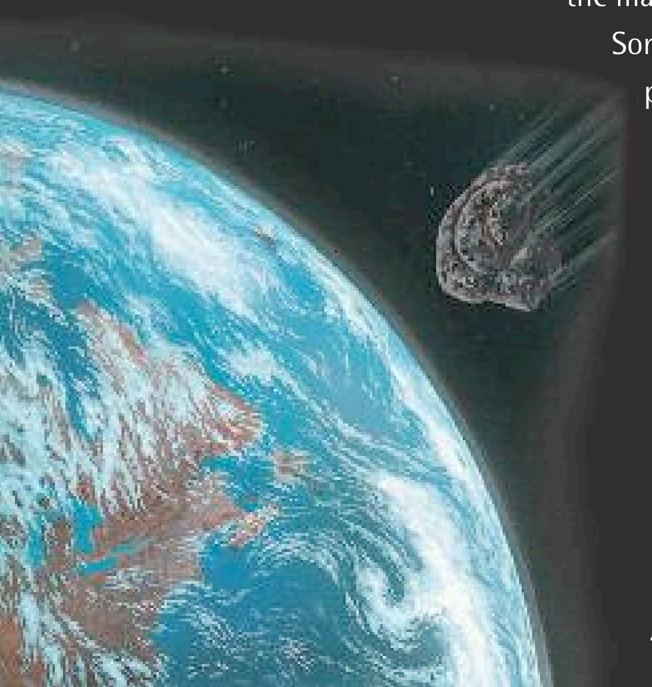
A 1.2-km-wide crater in Arizona, USA, made by a meteoroid much smaller than the K-T asteroid.

▲ Nearly all asteroids are irregular bodies, many covered with craters. Most are rocky, indicating that they come from the upper layers of a former planet. But a few are made of metal: they must have come from the cores of such a planet. Smaller fragments, known as meteoroids, produced from asteroid collisions, career around the Solar System.

Asteroids

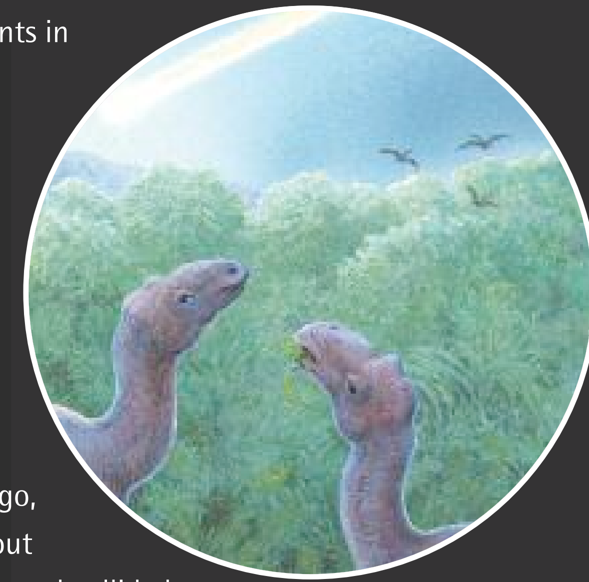
Orbiting the Sun inside the 550-million-km gap that lies between the planets Mars and Jupiter are millions of small, planet-like objects, called asteroids. Only a few asteroids have diameters of greater than 100 km across. Up to a million may have diameters of between 1 and 100 km, while countless others are little more than boulders.

Although most asteroids lie in a belt between Mars and Jupiter, a significant few have strayed from here. This may happen when large asteroids break up after a collision. The resulting fragments are then knocked out of the main belt and into other orbits around the Sun. Some, called Near Earth Asteroids, cross Earth's path. This, scientists believe, is what happened about 160 million years ago, when a large asteroid about 170 km across, called Baptistina, was struck by another, about 60 km wide. The cluster of asteroid fragments that was produced by the collision, scientists estimate, may have included 300 bodies larger than 10 km, and 140,000 larger than 1 km. Some of these fragments are still colliding with Earth today.



▼ The K-T asteroid approaches Earth

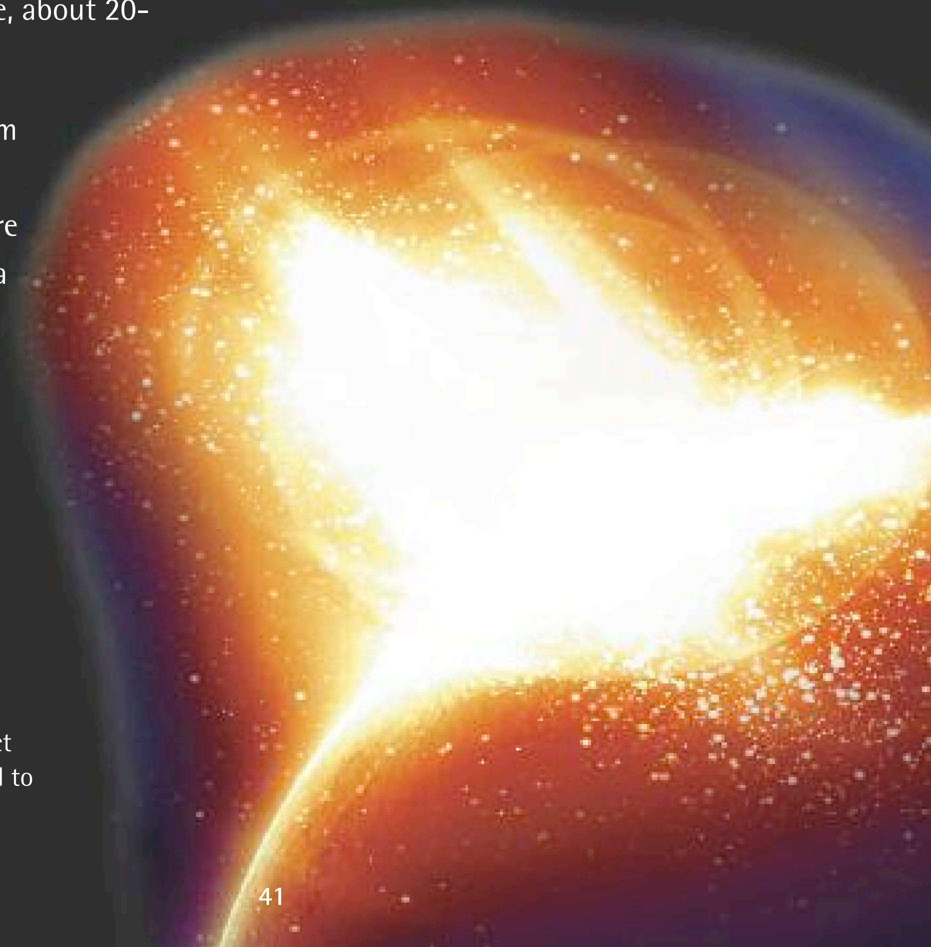
From studies of the sediments in the K-T boundary rocks, scientists can tell that the K-T asteroid *(opposite, centre)* had an unusual composition known as carbonaceous chondrite. This strongly suggests it came from the Baptistina family.



▲ Two *Edmontosaurus*, hadrosaurs, watch as an asteroid streaks towards the ground one fateful day, 65 million years ago.

One day, about 65 million years ago, this same asteroid, measuring about 10 km across, hurtled across space and collided with the Earth. Travelling at 30 km per second, 150 times faster than a jet airliner, it tore through the Earth's atmosphere and crashed into the ocean. Approaching from the southeast, it hit at a shallow angle, about 20-30 degrees.

Objects up to 10 m across strike the Earth's atmosphere on average once a year, but those the size of this asteroid hit Earth only once every 100 million years.



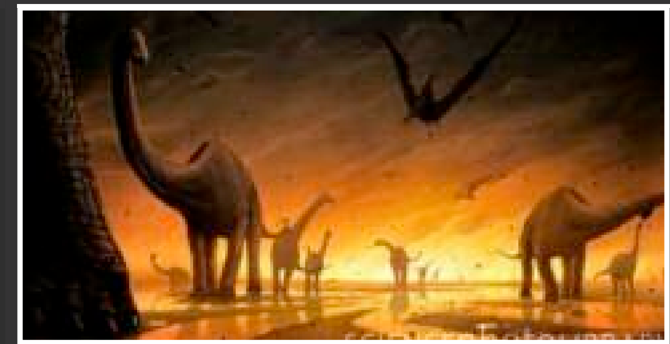
▶ The asteroid impact as it may have looked to an observer in space.

Impact!

It is impossible to imagine the force of the explosion at the moment the asteroid crashed to ground. The explosive energy released was equivalent to 100 trillion tonnes of TNT – over a billion times more explosive than the atomic bombs that destroyed Hiroshima at the end of World War II. The blast would have completely destroyed everything within a 500-km radius. The intense pulse of heat resulted in a firestorm, incinerating all living things for hundreds of kilometres.

Landing in the sea, shock waves set off some of the largest tsunamis the Earth has ever seen. Called "megatsunamis", mountainous waves some 1000 m high surged out in all directions, flooding the continents deep inland and triggering a chain reaction of volcanic eruptions, earthquakes and continental landslides that, in turn, generated further tsunamis. The asteroid itself, vaporized on impact, along with a sizeable chunk of the Earth's crust, was blasted into the upper atmosphere, blocking out the sun.

▶ On the ground, the massive explosion of rock and gas would have looked like a huge fireball filling the sky, frying any living creature within several hundred kilometres. Certainly any dinosaur in the area, big or small, would have met an immediate end.



Later, this would rain down all around the globe as vast quantities of super-heated dust and ash, igniting global wildfires. Sulphur dioxide, released from the gypsum rock the asteroid struck, billowed into the atmosphere along with all the rock fragments and dust from the impact.

Life in the sea

How did the asteroid impact affect life in the sea? Phytoplankton, microscopic plant life that floats in surface waters, would have suffered the same fate as plants on land and died out. This led to the collapse of the food chain on which large marine reptiles and many other species depended. Some scientists have suggested that acid rain, resulting from sulphur dioxide in the air, might have mixed with seawater, killing off many marine species. Later studies have shown this is unlikely to have had a significant effect, however.

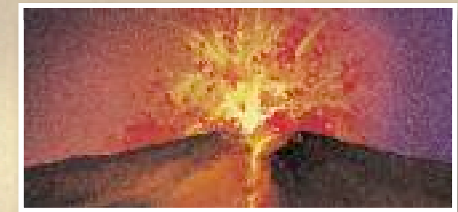
The long winter

Plant life, the animals that fed on plants, and the animals that fed on them — the entire food chain — was drastically affected by the asteroid impact and its immediate aftermath. The plant-eating dinosaurs died out when the plants on which they depended for food became scarce. Consequently, predators such as *Tyrannosaurus rex*, also perished. A number of environmental consequences of the impact may have been responsible for these extinctions.

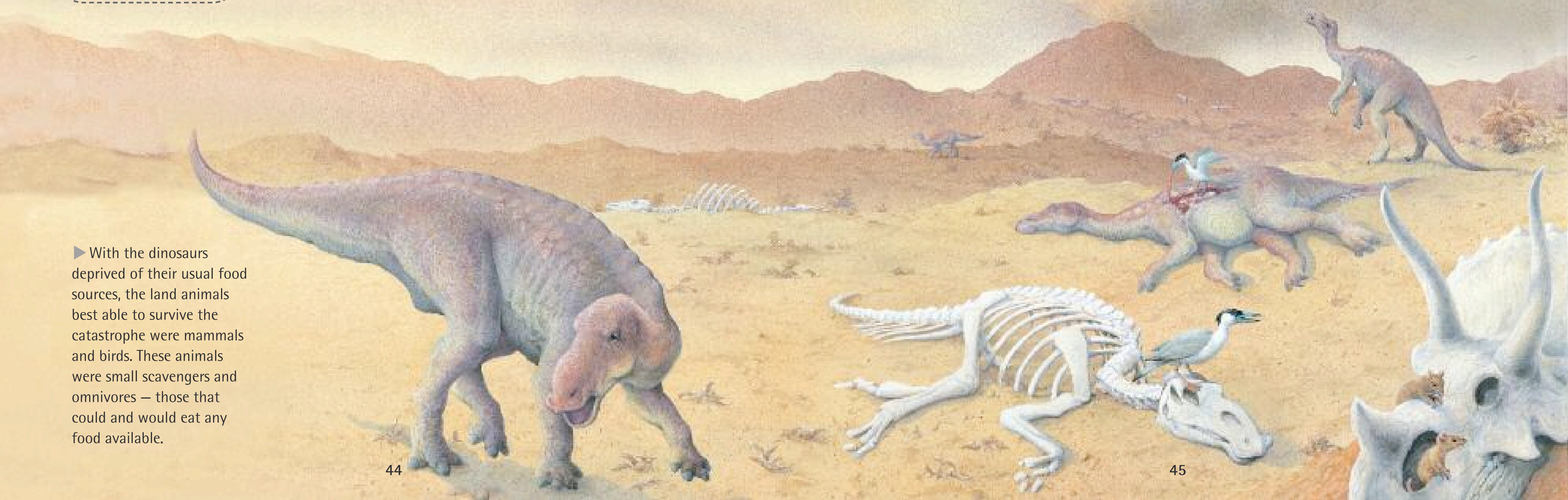
Ash and dust probably went on falling for several years after the impact, covering the entire surface of the Earth and creating a harsh environment for living things. Sunlight was blocked from reaching the surface by the dust particles and the sulphur dioxide in the atmosphere. Thus the Earth's surface was cooled dramatically for years, and photosynthesis by plants — the way plants make their food — was fatally interrupted.

It took at least ten years for the dust particles and sulphur dioxide in the air to clear. The loss of sunlight over this period would have been lethal for plants and plankton, and thus for all organisms dependent on them.

Whether the extinction occurred gradually (over a few thousand years) or very suddenly (within just a few years) is unknown. Even before the impact, falling sea levels and massive volcanic eruptions — both having a serious effect on dinosaur habitats — may have caused some species to die out. There is evidence to suggest that the number of dinosaur species was already declining quite rapidly in the last 10 million years of the Cretaceous period. Possibly the Age of Dinosaurs was drawing to an end anyway, and the asteroid catastrophe finished it off almost instantly.



▲ Some scientists have suggested that the eruption of a "super-volcano" may have caused the extinction of the dinosaurs instead. Massive and continuous eruptions are known to have taken place in the Deccan Traps region of India 65 million years ago. So much dust and ash was spewed into the air that cooling on a global scale took place. Whether this was catastrophic to life in the long term is now thought to be unlikely.



▶ With the dinosaurs deprived of their usual food sources, the land animals best able to survive the catastrophe were mammals and birds. These animals were small scavengers and omnivores — those that could and would eat any food available.

Survivors

What kind of animal could have survived an environmental disaster on this scale? Why did dinosaurs fail, while birds, mammals and even some other reptiles made it through?

Animals that could burrow, swim or dive would have been able to shelter themselves from the worst, immediate consequences. Crocodiles, the only other large land reptiles around besides the dinosaurs, survived because they could go for several months without eating, whereas dinosaurs could not. Lizards and snakes adapted to new habitats.

Birds and mammals possessed a number of advantages over dinosaurs. By being small, they could find shelter more easily: under the ground, in trees or in water and marshland. They could also survive on a meagre diet, scavenging for whatever food they could find in a harsh environment. Later, birds and mammals began to take over the dominant roles in nature that the extinct dinosaurs once held: large, herding herbivores, giant predators, and the rest.

▼ The first mammals evolved from reptiles about 205 million years ago. They lived through the Age of Dinosaurs as small, nocturnal creatures. Being insect-eaters, and able to shelter by burrowing or taking to aquatic habitats helped them to survive the asteroid impact.

▼ Ten million years after the last dinosaur breathed its last breath, some birds had evolved into giant carnivores not unlike mighty *Tyrannosaurus rex* itself. The flightless *Gastornis* was 3 m tall, and preyed on small horses, then only about 300 m high at the shoulder.

Glossary

Cretaceous Period of Earth history 145-65 million years ago. Much of the Earth was covered by shallow sea during the Cretaceous.

Dinosaurs Large land reptiles that lived 248-65 million years ago.

Extinction The complete dying out of a species. All the dinosaurs, and many other prehistoric creatures, became extinct at the end of the Cretaceous.

Fossils The ancient remains, or traces, of living things preserved in rock.

Gastroliths Stones in the gut of large plant-eating dinosaurs that helped break down tough plant material.

Hadrosaurs A group of plant-eating dinosaurs also called duck-bills.

Jurassic Period of Earth history 200-145 million years ago. Dinosaurs dominated the Earth during the Jurassic.

Mammals Warm-blooded vertebrates that have hair and mostly bear live young, which they feed with milk.

Matrix The surrounding rock in which a fossil is embedded.

Minerals Natural chemical substances that are neither plant nor animal. Rocks are made up of minerals. Minerals are the commonest solid material on the Earth.

Ornithischians The "bird-hipped" dinosaurs, one of two major types of dinosaur. Ornithischians had backward-sloping pubic bones – the lower part of the hip bone.

Palaeontologists Scientists who study fossils.

Reptiles Air-breathing, scaly-bodied vertebrates that evolved from amphibians. Dinosaurs were reptiles.

Pterosaur Extinct flying reptile.

Saurischians The "lizard-hipped" dinosaurs, one of two major types of dinosaur. Saurischians had forward-jutting pubic bones – the lower part of the hip bone.

Sauropods Long-necked, four-legged, plant-eating dinosaurs. They were the largest and heaviest land animals ever.

Sediments Eroded rock fragments that are transported by wind, water or ice and laid down elsewhere.

Tectonic plates The large slabs into which the entire Earth's surface is divided. The plates, 15 in all, move relative to one another around the globe.

Theropods All the meat-eating saurischian dinosaurs.

Triassic Period of Earth history 248-200 million years ago. The dinosaurs first appeared during the Triassic.

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