The Dinosaurs Rediscovered

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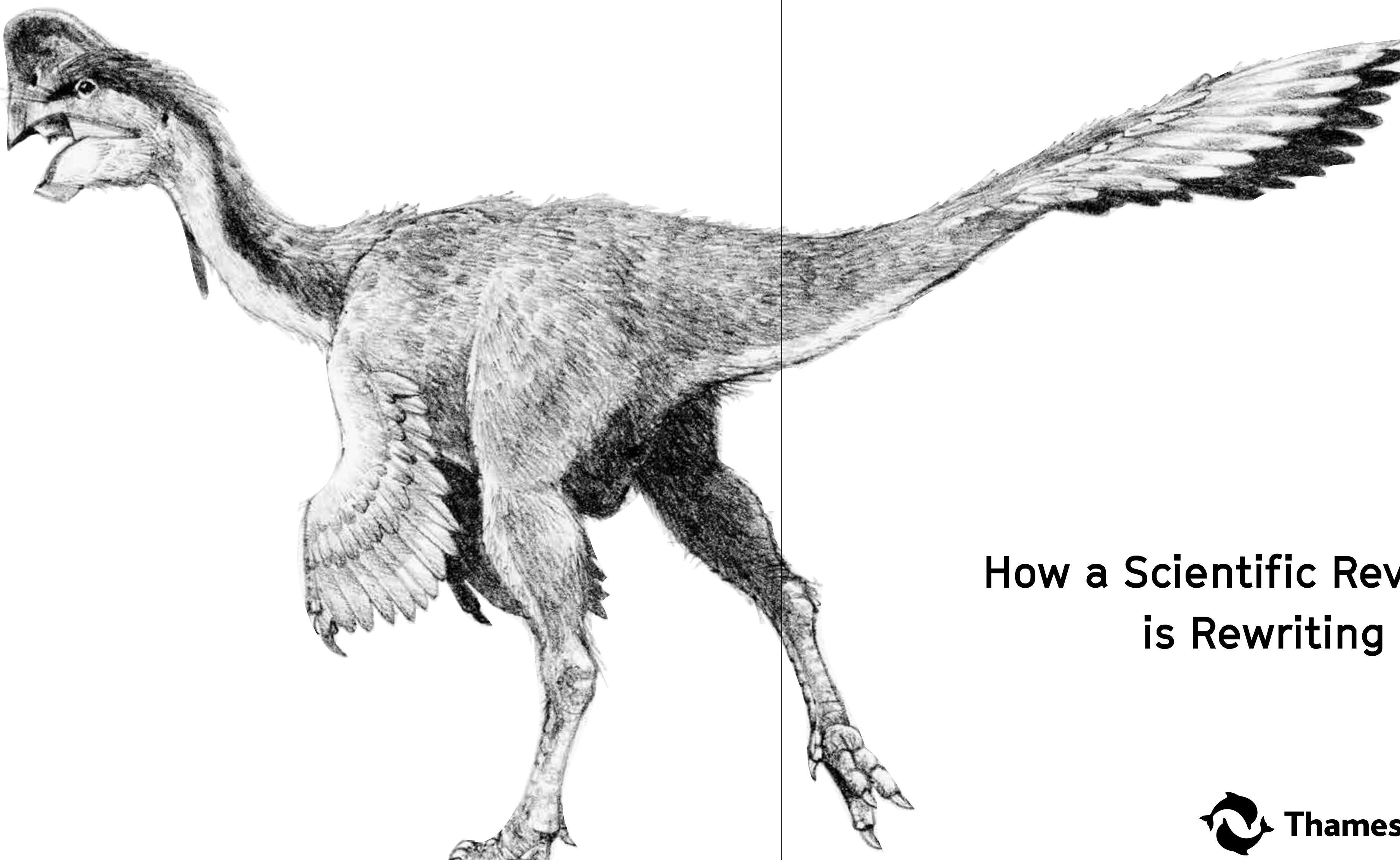

How a Scientific Revolution is Rewriting History

Thames & Hudson

Dedicated to my wife, Mary, and children, Philippa and Donald, for putting up with me.

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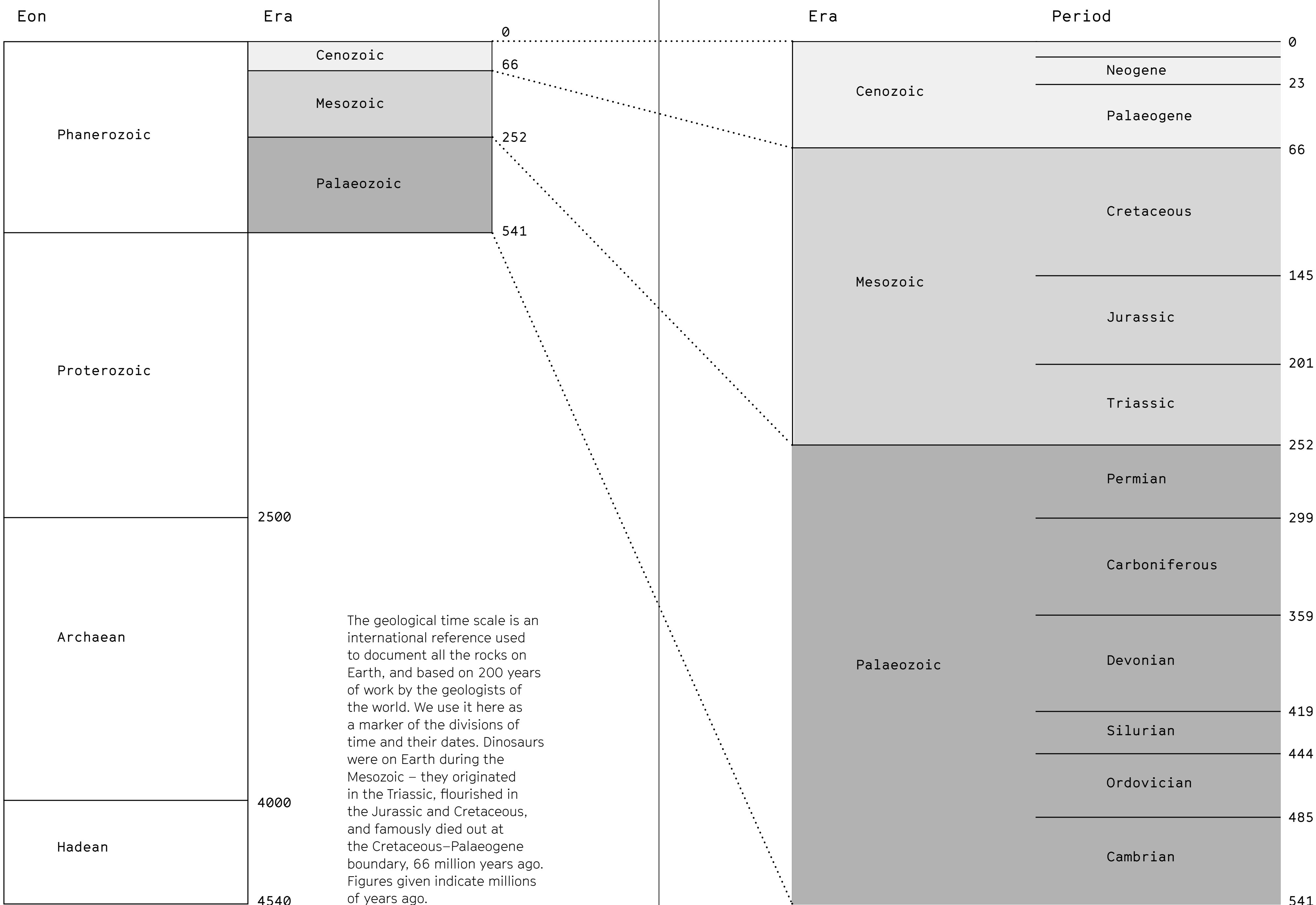


The geological time scale is an international reference used to document all the rocks on Earth, and based on 200 years of work by the geologists of the world. We use it here as a marker of the divisions of time and their dates. Dinosaurs were on Earth during the Mesozoic – they originated in the Triassic, flourished in the Jurassic and Cretaceous, and famously died out at the Cretaceous–Palaeogene boundary, 66 million years ago. Figures given indicate millions of years ago.

Introduction

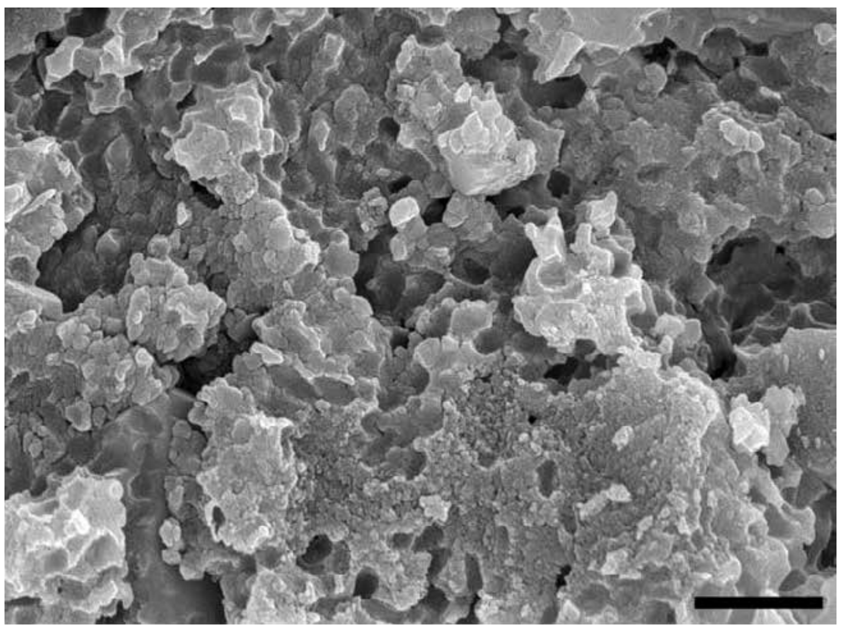
How Scientific Discoveries are Made

Discovery

I can remember the day – 27 November 2008 – when Paddy Orr came through from the scanning electron microscope (SEM) lab in Bristol, and said 'We've found these regular organelles in the feathers. What do you think they are?' I went through, and he, I, and Stuart Kearns, who runs the facility, checked over the tiny chippings from the feathered dinosaurs from China. There they were on the screen – rows of slightly distorted spheres deep in the feather tissue. As Stuart rolled the control ball, the field of view changed and wherever we looked there they were...

Melanosomes.

In a 125-million-year-old fossil feather.



Spherical melanosomes in a fossilized feather of the dinosaur *Sinosauropteryx*.

Melanosomes are the tiny hollows inside hairs or feathers that contain melanin. Melanin is a pigment that gives the black, brown, grey, and ginger colours to hairs and feathers. We were the first ever – or at least the first on record – to have seen evidence of melanosomes in dinosaurs. If we had got it right, this was evidence of the original colour of their feathers. We could say that for the first time we had discovered for sure the colour of a dinosaur.

We were torn by emotions at this point. Our first desire was to rush out and tell the world – call the press and shout from the rooftops! On the other hand, as scientists, we are trained to be careful, and we wouldn't want to look foolish by making such a wild claim if the evidence wasn't there. There's also a whole process behind publishing science, the so-called peer-review process, which ensures you present all your evidence, in detail, and sufficient to pass scrutiny of two or three independent colleagues. Only after publication in a scientific journal do you release your discovery to the mainstream media.

So, we went out for a beer, and planned to look at more specimens and make more measurements. This was a hugely controversial observation back in 2008. The microscopic structures could be melanosomes, as we thought, but the critics would shred us if we couldn't show multiple observations, and rule out all possible alternative interpretations.

Over the past thirty years, opinion has moved back and forth – these tiny structures in the feather tissue were interpreted as bacteria, or artefacts, or melanosomes...Sometimes they were like tiny balls – as here – and sometimes like tiny sausages in shape. At one micron or half a micron across (a micron, or micrometre, is one-millionth of a metre or one-thousandth of a millimetre), we were working close to the limits of the magnification capability of the SEM. Was there any way they might be inorganic artefacts, perhaps some mineral crystals that had entered the feather during its fossilization?

Earlier that year, Jakob Vinther, Danish by birth but at that time a doctoral student at Yale University, had published an important paper that showed how the micro-balls and micro-sausages in fossil bird feathers occurred only in dark-coloured areas in the fossil – they were melanosomes, not bacteria. He argued very convincingly that if they were bacteria that had invaded the feather to feed on minerals in the decaying specimen, they should be distributed equally all over the surface, on both dark- and pale-coloured stripes.

We accepted his view and immediately applied this brilliant insight to fossil specimens we had been working on with our colleague

Dr Fucheng Zhang from the Institute of Vertebrate Paleontology and Paleoanthropology in Beijing. Fucheng had been a postdoctoral researcher in Bristol in 2005; he had brought over examples of fossil feathers from dinosaurs and birds, and we had been studying them.

The feather chippings came from *Sinosauropteryx*, a slender 1-metre-long (3-foot) dinosaur with a long tail and short arms – not a flyer. But the *Sinosauropteryx* fossils preserved beautiful examples of whisker-like feathers along the back and as tufts down the tail. Melanosomes, we knew, were the hollows in the keratin protein of a feather into which the pigment melanin is inserted as the feather grows. Ball-shaped melanosomes in our samples showed *Sinosauropteryx* was ginger – it had a neat ginger and white striped tail.

We had objective evidence for the colour and colour patterns of a dinosaur. The bounds of knowledge had expanded into an area that a week before had been speculation.

Science beats speculation

This is the theme of the story that follows: how science has pushed back speculation in dinosaur science. Not so long ago, the only answers to questions about dinosaurian palaeobiology, such as 'How fast did this dinosaur run? Could this dinosaur crack bones in half? What colour was it?' were little more than guesses, even if informed ones. Now these are questions that can be tested with evidence. That's science, and the switch from speculation to science is a massive advance.

I have had the good fortune to live through this astonishing revolution, starting in about 1970, when the transformation of dinosaurian palaeobiology began. One by one the speculations about evolution, locomotion, feeding, growth, reproduction, physiology, and, finally, colour have fallen to the drive of transformation. A new breed of dinosaur palaeobiologist replaced the older ones, and they have applied a hard eye to the old speculations. Smart lateral thinking, new fossils, and new methods of computation have stormed the field.

Beginnings

Like so many, I became fascinated with dinosaurs when I was young. When I was seven, I was given a classic little book, *Fossils, a Guide to*

Prehistoric Life, by Frank Rhodes, Herbert Zim, and Paul Shaffer. What excited me was that the illustrations were all in colour – unusual still in the 1960s – and that there were not only pictures of fossils, but reconstructions too. The text reflected the knowledge of the time – this is what *Tyrannosaurus* looked like, based on the classic studies by Professor Henry Osborn of the American Museum of Natural History, and this is how the dinosaurs died out, rather slowly, and perhaps as a result of long-term cooling climates (or maybe simply because they were too stupid to adapt to a changing world), according to the ideas of Professor Leigh Van Valen of the University of Chicago.

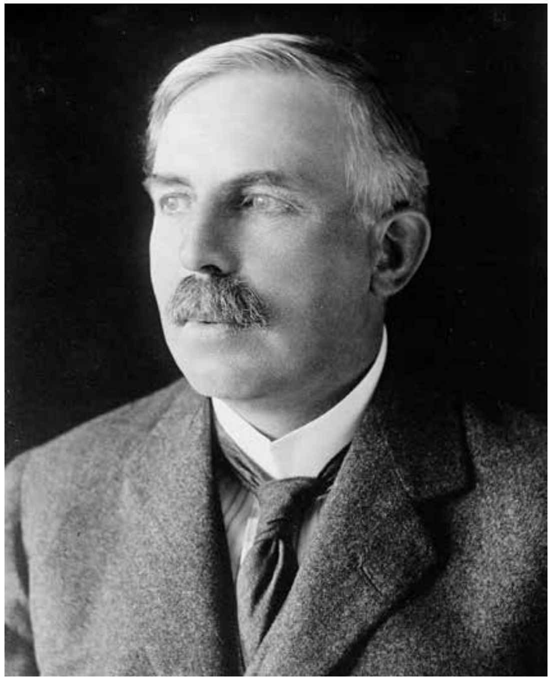
The assertions were clear, although the only reasons given for why we might wish to accept or reject the explanations was that they were the views of distinguished professors at distinguished addresses (and sometimes with distinguished beards).

Nonetheless, as a seven-year-old, that was all I needed. It never entered my head to question the authority of something written in a book, especially since most of the key information in Rhodes, Zim, and Shaffer was widely repeated. In any case, what could Professors Osborn and Van Valen actually have done in order to test what *Tyrannosaurus* looked like or how the dinosaurs died out? Dinosaurs are long-dead animals, represented now by skeletons and isolated bones. The extinction of the dinosaurs happened 66 million years ago, so how on Earth could a scientist hope to investigate it scientifically?

What is science?

This was the point being made by Sir Ernest Rutherford – the New Zealand-born physicist who made his name at the University of Cambridge with the discovery of the half-life of radioactive elements – when he stated, around 1920, that 'all science is either physics or stamp collecting'. Many hard-nosed physicists might agree with him even today. Nonetheless, he was ruling that much of chemistry, biology, geology, and the applied sciences in medicine and agriculture was not scientific.

I'm sure Rutherford viewed the sciences in a series, reading from left to right from 'strong' to 'weak'. At the strong end were mathematics and physics – his sciences, where experiments are designed and can be repeated with the same outcomes endlessly. These are the sciences where theory consists of equations that can be proved as universal laws, such as gravity or the electromagnetic theory of light. At the other end



Sir Ernest Rutherford, Nobel-prize-winning physicist, and a man with strong views about what is (and is not) real science.

of the spectrum would be the so-called 'soft sciences' such as sociology, economics, and psychology.

I expect Rutherford was also thinking about the popularity of nature among the Victorians, and how the amateur botanists, sea-pool scourers, and fossil-hunters went out at weekends to collect stuff. Indeed, collecting specimens for their beauty or for the satisfaction of completing a list ('I've seen all the birds listed in the handbook') is not science. What if they were writing down new information, say a new record of a rare butterfly; that was hardly pushing back the boundaries of science, was it?

What about the historical sciences, such as geology and palaeontology? They focus on long-past events, such as the origin of the Earth, the 'Cambrian explosion', when so many organisms suddenly appear in the fossil record, the origin of the dinosaurs, or the origin of humans. These are singular events that cannot be repeated. Nor can we go back in a time machine to see what was really going on.

Other historical sciences include archaeology, of course, and physical geography (the history of climates and landscapes), but also the parts of astronomy and cosmology that deal with the origin and function of the universe, and much of biology, which explores the evolution and function

of groups of plants and animals, their ecology and behaviour, as well as unique adaptations and their genetics.

The great philosopher of science Karl Popper gave the answer in 1934, in one of his most important books, *The Logic of Scientific Discovery*. In this, he argued that hypotheses are unlimited, but they must be open to refutation, through his so-called 'hypothetico-deductive method'. Hypotheses can only ever be falsified; they can never be proved. So, if Professor Smith declares, 'My hypothesis is that *Tyrannosaurus* was purple with yellow spots', that is not really a hypothesis because he provided no evidence, and so it can neither be proved nor disproved; it's a belief. (Note, however, we would argue that when we said *Sinosauropteryx* was ginger and had a ginger and white stripy tail, we were doing so scientifically and in a way that could be disproved by another scientist who might fail to find the melanosomes we claimed as evidence.)

In time, Popper explained, the accumulation of evidence corroborates a hypothesis. However, that well-supported hypothesis can then be disproved by a single fact. He gave the example of the swan, once thought – or hypothesized – to be white as a fundamental biological adaptation so they can be camouflaged against the winter snows. But the discovery of a species of black swan – such as the Australian black swan, first encountered by European naturalists in the seventeenth century – disproves the hypothesis, or at least adds a qualification: 'Not all swans are white, and so the camouflage model does not apply to the Australian Black swans.' Popper's key point was that anything that can be set up as a series of testable hypotheses (his hypothetico-deductive method) qualifies as science, and so sociology, economics, psychology, and indeed palaeontology are science if framed correctly.

I have been a little unfair on Rutherford here, as he would have accepted much of what Popper said. He was making a more restrictive claim about general laws. Geologists and biologists have struggled to formulate any universal laws of their subject.

For example: evolution is a universal principle, or set of processes, underlying the entire history of life, as well as modern phenomena such as the evolution of resistance to drugs and pesticides by disease vectors and crop pests. So, evolution is universal and it works, and it provides a vast overarching framework within which thousands of scientists operate throughout their professional lives. But it is not a universal law like gravity or the electromagnetic theory of light; exact predictions cannot be made. Gravity and light are predictable whatever the circumstances, but evolution depends on all sorts of unpredictable factors of organism and environment.

What methods and evidence do palaeontologists use?

When I was a student of biology at the University of Aberdeen in 1976, these concerns were far from my mind. I merely wanted to be a palaeontologist, to be paid (eventually) for doing what I loved – collecting fossils, drawing ancient creatures, and reading about dinosaurs endlessly. We were taught all the subjects in biology, how plants and animals worked, their evolution, ecology, and behaviour.

Then, we had an unusual series of lectures from a professor of the old school – indeed, he probably was not a professor – a wonderfully wrinkled and ancient-seeming man called Phil Orkin. (Checking the University records, I find Phil was born in 1908, and so was sixty-eight when he taught us; he died, aged ninety-six, in 2004, having been at the forefront of leading the small Jewish community in Aberdeen for years.) We were shocked by some of what he told us – that the facts we were learning were probably wrong and would be improved, corrected, and rejected in future.

As students, we struggled with his lectures because they were delivered without notes, and he did not give handouts. Still, Orkin did make us think about what we were being taught – all knowledge is provisional, he told us, and we must strive to make accurate observations. If we eventually made an observation that could overturn an accepted hypothesis, we had better be sure our observation was accurate.

What do palaeontologists have at their disposal? They have fossils, and the rocks from which the fossils come, as well as microscopes to look for fine-scale structures in those fossils – like our melanosomes. They also have methods from engineering, physics, biology, and chemistry to apply to their fossils. Fieldwork supplies great data.

For example, in the 1990s, I was working with Russian colleagues in the red beds of the Permian and Triassic around Orenburg, on the boundary of Europe and Asia. These 'red beds' (so-called because they are beds of rocks such as mudstone and sandstone that are red in colour) extended over hundreds of kilometres, documenting long spans of time through the Permian–Triassic mass extinction, which happened 252 million years ago. As we collected fossils, we also recorded the successions of sediments in detail, and collected samples every metre (3 feet) or so for laboratory analysis. We wanted to find out the geochemistry of the samples, to record the levels of oxygen and carbon throughout the succession in order to give information about the climate

and atmosphere, and especially to focus on the time of the great mass extinction, when some 95 per cent of species on Earth died out. We also recorded the orientation of the north magnetic pole through the rock succession, using methods of magnetostratigraphy – from time to time, Earth's magnetism has reversed polarity, so that the north and south magnetic poles have flipped. These crises mark time lines, and so can be used for dating the rocks against a world standard.

The data we were collecting in Russia allow geologists and palaeontologists to test how long the extinction event took, and whether it was one event or many – in fact, there were two bursts of extinction then, separated by 60,000 years. These observations require great care and sophistication in analysis and, together, they provide the essential framework for scientists to explore what caused that catastrophic loss of life and how life recovered (I wrote about this in *When Life Nearly Died*, 2015).

We collected various kinds of fossils in Russia, along the banks of the mighty Ural and Sakmara Rivers, which drain water from the Ural Mountains to the north, and erode down through the Permian and Triassic red beds. The ancient sediments included *body* fossils, skeletons and shells, and *trace* fossils such as tracks and coprolites (fossil faeces). Tracks can show details of soft tissues, such as the pattern of skin on the sole of the foot, and they record the *behaviour* of one or more animals on a particular day 250 million years ago; we can even estimate the speed of the beast from the spacing of its footprints. In Russia, we did not find any exceptionally preserved fossils, showing skin or feathers, for example, but such fossils, as in the case of our Chinese dinosaurs with feathers, can be crucial for palaeobiological interpretations.

Testable methods: bracketing

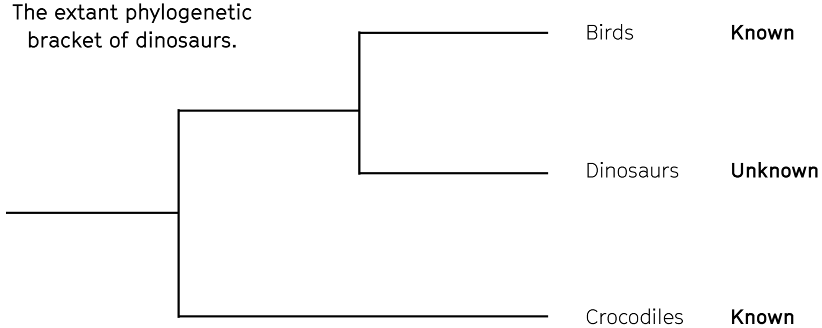
In making his comments about the feeding behaviour of *Tyrannosaurus*, Professor Osborn referred to modern predators such as lions and hunting dogs. Their behaviour may give us clues about how extinct animals behaved. For example, many hunting dogs today are too small to bring their prey down with a decisive bite to the neck, as a lion or tiger might. So, a small pack of wolves in Canada may follow a moose and snap at its leg tendons trying to break them and so cripple the animal. The wolf could be killed any moment by a kick from the moose, so it has to circle and rush in fast to deliver a bite. After many miles of chase, the exhausted moose may collapse, and the wolves can at last kill it and feast on its flesh. These observations provided ideas for how smaller predatory dinosaurs might have harried their larger prey.

In these cases, the palaeobiologist is using *modern analogues* as a way of making believable, and vivid, his or her assumptions about the fossils. In some cases, study of the modern analogues points the palaeobiologist at things to seek in the fossils. Maybe pack hunting cannot be determined in a dinosaur skeleton, but hunting modes may be deduced from the frequency of broken and damaged bones found in the hunters – were they risk-takers, like modern wild cats and dogs, leaping at larger prey and risking injury?

There is a key question, though: how do you choose your modern analogue? If you are trying to understand the hunting tactics of *Tyrannosaurus rex*, is the wolf, as a mammal, a good analogue? Would an example of hunting behaviour from a lion or eagle, or even from a shark, be equally useful? This question was left unanswered until 1995.

In that year, Larry Witmer argued that an insight he had developed would allow us to say a great deal about every unpreserved detail of, say, *T. rex*. We could describe its eyeball, its tongue, its leg muscles, even its behaviour around egg-laying and hunting. Witmer's insight is called the *extant phylogenetic bracket*. (Phylogeny is the evolutionary history of an organism or organisms.) He reasoned that, if the analogues were well chosen, they could tell us a great deal. For example, in the evolutionary tree, birds and crocodiles are close relatives – they are all archosaurs ('ruling reptiles'), together with the dinosaurs. If crocodiles *and* birds share some detail of the eyeball or the leg muscles, then dinosaurs had it too. We can't say dinosaurs had feathers simply because birds have feathers – crocodiles do not have feathers, so dinosaurs are not bracketed as far as that character is concerned. That's why we can confidently describe the form and function of the eyeball of *T. rex* – not because

The extant phylogenetic bracket of dinosaurs.



of random comparisons with lions or sharks, but because crocodiles and birds, which bracket the dinosaurs in the evolutionary tree, share most features of eye structure and function. Likewise, we can say that *T. rex* probably showed some minimal parental care after its babies hatched – because crocodiles and birds both share this behaviour.

I can give a concrete example that was crucial in our work on the colour of dinosaur feathers. We studied how colour is expressed in modern bird feathers, and how the different kinds of melanin, the black-brown kind and the ginger kind, are associated with different microscopic organelles. Black-brown melanin is packed into sausage melanosomes, ginger melanin into ball melanosomes. We saw this in bird feathers, and it was always the same. It's also true of all mammals, including humans. In the evolutionary tree, dinosaurs, and most other extinct reptiles, are bracketed by birds and mammals, so this is a universal relationship. Therefore, when we saw the ball melanosomes in *Sinosauropteryx*, we thought, birds have these, mammals have these, and so this works for the bracketed dinosaurs too. *Sinosauropteryx* had ginger feathers.

Testable methods: engineering models

Another testable method in palaeobiology is the engineering analysis of digital models. A digital model is a perfect 3D rendering of an object inside a computer. The model can be rotated and magnified, and the analyst can fly in through the left eye socket of the digital *Tyrannosaurus* skull, and out through its mouth, before returning through the right nostril to explore inside the nasal cavity. The secret to testability is to map the correct material properties onto the bone – in other words, the material properties of bone, as calculated from modern bone: what force it takes to smash a 1-centimetre (⅜-inch) cube of bone, and how far a bone of a certain diameter can be bent before it snaps. Then the engineering analysis can begin.

For her doctoral studies in Cambridge, UK, Emily Rayfield had to work out the form and function of the skull of *Allosaurus*, a large predatory dinosaur of the Late Jurassic. She scanned the skull, and repaired it by replacing missing and damaged bones and removing distortion to create the perfect 3D digital model of the skull. She then assigned material properties to different parts of the skull – hard and brittle for the enamel of the teeth, softer and more pliable for parts of bone around the sides of the skull.

To assign material properties the skull is divided into pyramidal 'cells' or elements, and then a classic engineering method can be applied, *finite element analysis* (FEA). This is the method used by architects and civil engineers to stress-test their designs before beginning construction. Every skyscraper, bridge, or aircraft to which you entrust your life has been pre-tested using FEA.

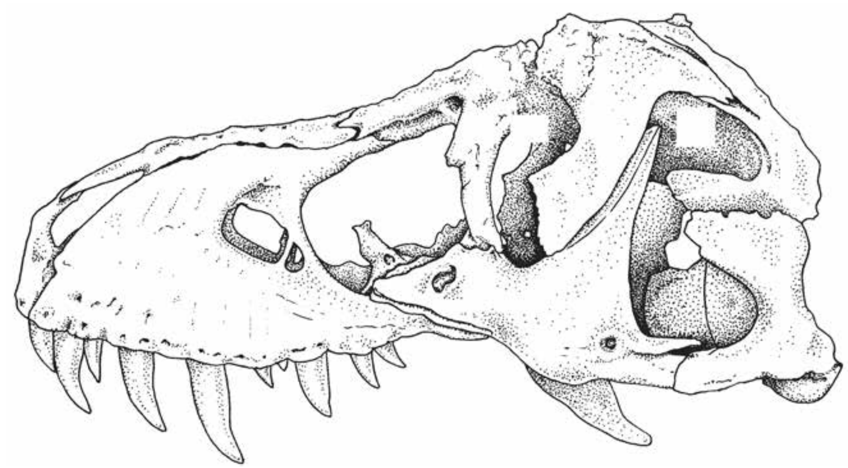
The argument is that we know the method works. The digital model of a future skyscraper, bridge, or aircraft is stress-tested to see at what point of applied pressure it breaks. This is the basis of the engineering design of the structure before it is completed, and we live in skyscrapers and fly in aircraft designed this way, trusting that the calculations were correct. Therefore, if we use the same approach to study a dinosaur skull or leg, we should accept the results as true. Inside the computer is a perfect functioning model of the extinct animal. This is a pretty amazing claim – that palaeobiology is testable science. Even Ernest Rutherford might have accepted that we can now turn some parts of palaeobiology into rigorous, hard science.

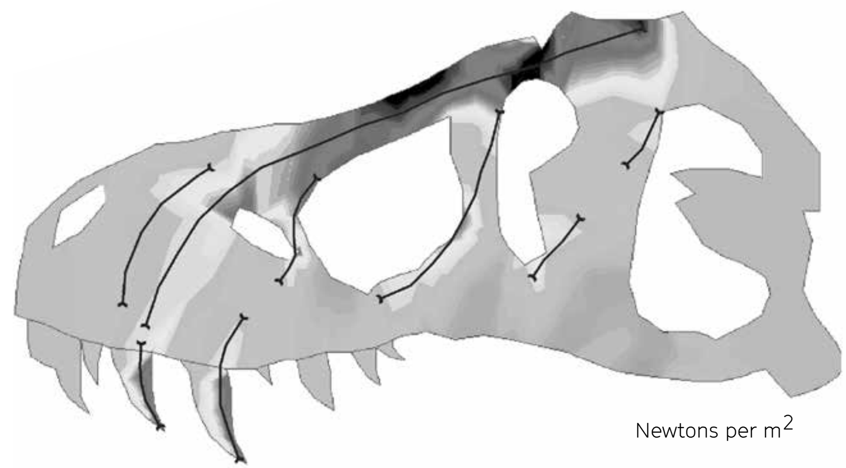
The revolution

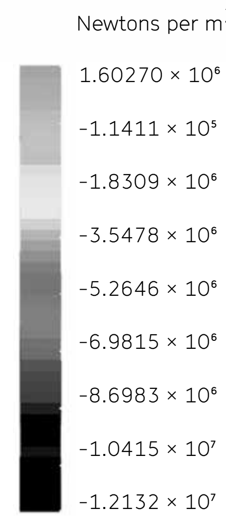
I have lived through a revolution. When I started as a student some forty years ago, palaeobiology was a practical subject aimed at solving problems for the oil industry – especially relevant in the town where I grew up, Aberdeen. The granite city was experiencing massive economic growth as a result of the North Sea oil boom. If my professors talked about form and function or evolution, they did so a little apologetically, because they were straying from hard facts.

Through my scientific career, I have seen dinosaur science (and palaeobiology in general) change from natural history to testable science. New technologies have revealed secrets locked in the bones – we can now work out the colour of dinosaurs, their bite forces, speeds, and levels of parental care. I have taken an active part in the debates about reconstructing the tree of life, the Jurassic Park phenomenon and the viability (or not) of dinosaur DNA, the CT scanning and digital imaging revolution, and new engineering models to test the bite force and running speed of *T. rex*, as well as the colour of dinosaurs.

Much of the press coverage of modern palaeobiology focuses on remarkable new fossil finds, such as giant sauropod dinosaur skeletons from Patagonia, dinosaurs with feathers from China, and even a tiny







The skull of *T. rex* (above) and a digital model that enables the skull to be stress-tested (below). In the lower diagram, the darkness of shading indicates the amount of stress, with light greys indicating high stress.

dinosaur tail in Burmese amber. New fossils are the lifeblood of modern palaeobiology, of course, but it is the advances in technologies and methods that have driven the revolution in scope and confidence.

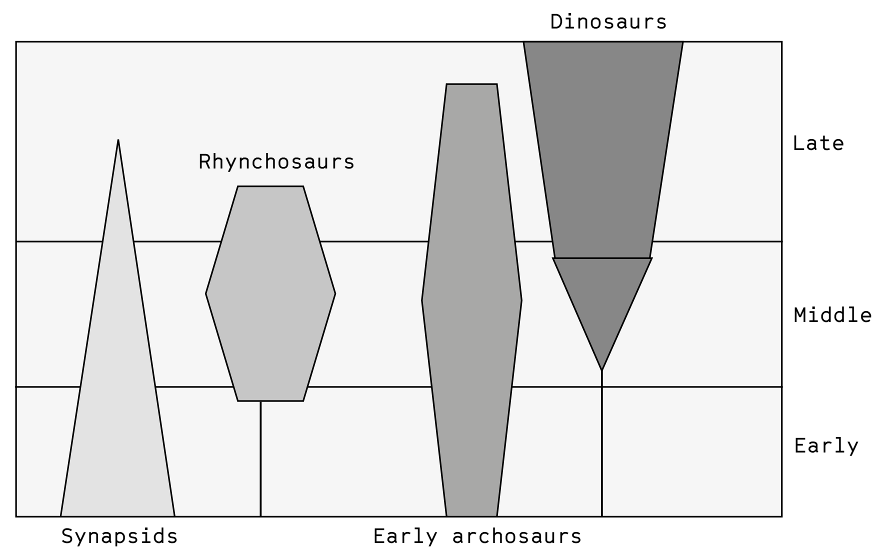
The aim of this book is to show all the latest amazing fossils, and to take the reader behind the scenes on the expeditions and in the museum laboratories. The key theme throughout is the transformation of a historical science from its roots in Victorian natural history to a highly technical, computational, and thoroughly scientific field today. These have been exciting times of rapid change and astonishing new discoveries, happening at a rate never seen before.

Chapter 1

Origin of the Dinosaurs

One thing is known for sure: the dinosaurs originated during the Triassic period, between 252 and 201 million years ago. Nearly everything else is uncertain. For example, just when did they originate, in the Early or Late Triassic? What was the world like as they emerged on the scene? Did they force their way to dominance of global ecosystems by fighting hard for their place against other beasts, or did they achieve their position by good luck? When I began my career as a palaeontologist, back in the 1980s, these were all hot topics of discussion. Solving the questions has been my life's work, but I can't say everything is sorted out: whenever one problem is resolved, further questions are raised. It's a story of changing ideas about evolution, new fossils, and new analyses.

As part of my doctoral studies I tried to work out an ecological model for the origin of the dinosaurs. The 'standard' model then was a three-step process. First, the synapsids, ancestors of mammals, were the key herbivores and carnivores. Then, the synapsids were replaced



The classic model for dinosaur origins by progressive competitive replacements in the Triassic.