Requiem
Katie Paterson

Ingleby Gallery, 9 April – 11 June 2022
National Glass Centre, 17 June – 11 September 2022

Billion Years	
<4.6 Byr	PRESOLAR
4.54-4 Byr	HADEAN
Million Years	
4540-539 Myr	PRECAMBRIAN
539-487 Myr	CAMBRIAN
487-443 Myr	ORDOVICIAN
443-419 My	SILURIAN
419-359 Myr	DEVONIAN
359-299 Myr	CARBONIFEROUS
299-252 Myr	PERMIAN
252-201 Myr	TRIASSIC
201-143 Myr	JURASSIC
143-66 Myr	CRETACEOUS
66-56 Myr	PALEOCENE
56-34 Myr	EOCENE
34-23 Myr	OLIGOCENE
23-5.3 Myr	MIOCENE
5.3-2.6 Myr	PLIOCENE
Years	
2,580,000-11,700 yr	PLEISTOCENE
11,700 yr-1945 CE	HOLOCENE
1945 CE-PRESENT	ANTHROPOCENE

PRESOLAR
<4.6 BYR

1 (< than 4.6 Byr)
Dust from before the Sun existed

A meteorite – even more than most rocks – is a mashup of time and space. Those which are called the carbonaceous chondrites are the oldest; they stretch the furthest back in time, and across the farthest distances. They include, here and there, tiny specks called *presolar grains*, tiny mineral fragments that formed as ancient giant stars exploded, and that drifted in clouds, eventually to reach our corner of the galaxy, raw material for new star systems. The stardust particles nestle against other grains that formed from melted dust as our own Solar System was born and our Sun started to shine, 4,567 million years ago. It's a spookily easy age to remember (and one worked out from little atomic timekeepers that started ticking into those grains, all that time ago). It would take a little longer (and many collisions of the whirling space debris) for the Earth itself to form – but the carbonaceous chondrites brought to it carbon, too, and so the stuff of future life. After that stellar beginning, things settled down a little – and much, much later, that living Earth was to be the landing place for the meteorite, a late-arriving piece of stray space debris, that forms the first layer of Katie Paterson's artwork, *Requiem*.

HADEAN
4.54-4 BYR

2 (4.55 Byr)
Lunar dust combined with material from the asteroid Vesta

Before the Earth, there was the protoplanet Tellus, but we cannot reach back to this planetary ancestor, because it has gone, destroyed by impact with another planet, the onrushing Theia. This, it is thought, was the real beginning of our Earth, and also of the Moon, born in one cataclysmic instant about 4.5 billion years ago. Theia might have brought with it much of the water of our oceans too, as an additional gift. A delayed gift, though, for after the giant impact, the Earth would have been incandescent, with a thousand-kilometre-deep ocean, not of water, but of magma. Only when our planet cooled could the steam around it begin to condense into the beginnings of the deep blue sea. On clear nights, simply by looking at the Moon, we can reach back through this history. We can touch it, too, here – through the glass of this urn – in this layer with its ground-up lunar dust.

3 (precise ages unknown)
Earth's crust, mantle, and core: a mix of peridotite, labradorite plagioclase feldspar, and volcanic bomb
France and Hawaii

The Earth's three layers – core, mantle, and crust – were set in place in that thunderous impact with the doomed planet Theia, deep in the Hadean. The core is far too deep to sample, but volcanoes can bring up mantle lumps dragged from deep with the onrushing magma, as in the block of peridotite from France now in this layer. To symbolise the first crust, there is here also a piece of labradorite, of the feldspar family of minerals. A relatively light mineral, too, billions of such feldspar crystals likely rose to the surface of the global magma ocean following the Theia impact to form the first solid crust on planet Earth, a distant precursor of our continents. There's nothing left, now, of this primordial crust on Earth – but look up at the night sky, and the bright patches on the Moon, its ancient Highlands, are made up of such a rock. Ocean crust is a little harder to get it, most being far below sea level. But there are places where the ocean crust builds up as volcanoes, to break through to the ocean surface and sometimes, as with Hawaii, to climb to more than four kilometres above sea level. The Hawaiian volcanic bomb also present here is of dark, heavy basalt, which overwhelmingly dominates the ocean crust, and which is also abundant, we now know, at the surface of the Moon (making up its 'seas') and on other planets in the Solar system. Basalt may be a universal rock cosmically, as well as on Earth.

PRECAMBRIAN
4540-539 MYR

4 (4.4 Byr)
Zircon, Metaconglomerate Narryer Gneiss slice
Jack Hills, Australia

The first billion years of the Earth is a mystery – literally lost in the mists of time. Almost everything of those first landscapes has gone, chewed up and transformed by some kind of tectonic transformation (which we still don't quite understand) into newer and more familiar rocks. The ultra-rare survivors are tiny – and very, very tough. They are a thimbleful of zircon crystals, each the size of a mote of dust. They formed from 4.4 billion years ago – and so just a hundred million years into Earth's history – in magma chambers deep within the Earth's crust. But their chemistry hints that, far above, the Hadean Earth already had primordial oceans. Later, these tell-tale zircons were eroded out of their magma chamber and into a sandstone – a mere three billion years old – in the Jack Hills in Australia, and much later they were hammered out of those sandstones by curious geologists (and one or two have wound up in this urn). Many will keep travelling, until the end of the Earth.

5 (4.1-4.2 Byr)
The oldest known rock on Earth: Acasta Gneiss
Canada

The Acasta Gneiss is generally held to represent the oldest rocks on Earth, dating back to 4 billion years, and thus the very end of the enigmatic Hadean Eon. But what kind of rocks are these? The kind of rock that you see now is not what it originally was, having been subsequently deeply buried, heated to the point of *almost* melting, stretched, squeezed, crumpled, and generally scrunched (almost) beyond recognition. Some of the minerals – including those hardy zircons – suggest, though, that at least some of the original rocks were granite-like, having crystallised in a magma chamber deep below the ground surface. As to what that ground surface was like… well, that's still a mystery.

6 (3.8 Byr)
Fuchsite, containing water and Archean gold
Isua Greenstone Belt, Greenland, Danish Geological Survey GEUS

The ancient rocks of Greenland are of more than abstract interest. Within them are deposits of gold that have already caught the attention of human fortune-seekers. There is a particular pattern to this gold in the Isua rocks, where it is tangled up with quartz, and calcium carbonate, and an otherwise obscure kind of mica called fuchsite, which is chromium-rich. When gold is found together with these minerals elsewhere in the world, it is thought to have been sweated out as one of the by-products of plate tectonics, carried by hot subterranean waters from deep-lying collision zones of tectonic plates, and crystallising in the rocks high above. So that could mean – some geologists have mused – that already 3.8 billion years ago, when the Isua rocks were forming, modern-style plate tectonics was already operating on Earth. But be warned! The enigma of the early Earth is like a classic detective story, laden with ambiguous clues, red herrings, false trails, and witnesses – the rocks themselves in this case – who are hell-bent on leading the detective astray.

7 (3.7 Byr)
Gneiss metamorphic rock
Isua Greenstone Belt, Greenland

The Isua rocks of Greenland *used* to be celebrated as the Earth's oldest – that is, until the geologists turned up Canada's Acasta Gneiss. They are still very old, at 3.8 Byr, and so in the early part of the Archean Eon where Earth's geological record really begins. Although not quite as terribly mangled as the Acasta rocks, they have suffered enough of the ravages of time and heat and pressure to be difficult for geologists to read, and so controversies abound. Do they preserve a record of the Earth's surface? Well, perhaps, as the remains of lavas have been found, that erupted on to some deep (it's thought) sea floor. Do they preserve evidence of *life*? This is much more debatable. Some geologists have pointed to structures in the rocks that they think are the petrified remains of ancient microbial mats. Others, though, disagree, saying that these supposed fossils are just tectonic crumples in the rock, that formed deep underground when the Isua strata were caught up in some ancient mountain building episode. This remains a mystery.

8 (3.5 Byr)
Beginning of modern-style plate tectonics: Komatiite, magmatic rock
Komati river, South Africa

In Archean times, three billion years ago and more, the Earth was hotter than it is now: its huge bulk still retained some of the heat of the impacts of meteorites and planetesimals that had created it – including that mighty collision with planet Theia – and its interior was also more radioactive. So volcanoes ran hotter too. One symptom of this was a particular kind of lava, called a komatiite, named after the Komati River in South Africa, where particularly good examples are found, and where this urn layer comes from. This rock is a little like a basalt, but one with a different chemistry (it has lots of magnesium in it) and which erupted onto the Earth's surface at some 1600 degrees centigrade, several hundred degrees hotter than typical basalts today. It would have been quite a sight! An incandescently, dazzlingly white-hot lava, denser than other lavas but nearly as runny as water, and so making flows that run fast but may be as little as a centimetre thick. It's a spectacle that – perhaps fortunately – became less and less common as the Earth cooled over billions of years, to be last seen (to our knowledge) in the times of the dinosaurs. What is left are these charismatic fossil lavas, which often have crystals in them with the appearance of huge needles. It's a sign that the Earth, then, really was an alien planet.

9 (3.4 Byr)
First definitive life: Stromatolite
Strelley Pool Formation, Australia

When did life begin? The evidence from the early Earth is so ambiguous and so elusive, and scientists have been so prolific with ideas and counter-ideas, that one could write a very, very large book on the subject. There have even been suggestions that life might have emerged on Earth in the depths of the Hadean, more than 4 billion years ago, as some of the Jack Hills zircons are thought to have crystallised – in a magma chamber deep below ground, no less! – with tiny scraps of life-derived carbon within them. That's a very long shot, and most geologists are sceptical of this as evidence of life. But most geologists are reasonably convinced by the evidence from somewhat later in time, from some 3.4 billion years ago, when a curious seascape, looking a little like various kinds of lumps, mounds and egg-cartons, took shape in what is now the Strelley Pools area of Australia. That's now preserved as layers of limestone, and this particular kind of layering is thought to represent *stromatolites*: hardened rock layers formed by microbial mats carpeting that sea floor. Furthermore, microscopic remains of microbes have also been found at Strelley Pools, and so it seems pretty clear that – long, *long* before the dinosaurs – the Earth was already a living planet.

10 (3.2 Byr)
Sedimentary rock from the Banded Iron Formation
Barberton, South Africa

Taking a time machine to the seaside in the Archean would be quite an experience. Some things might look pretty similar. The Sun in the sky, for instance, the blue skies and clouds (and rain showers too) and sand on the beach. But you would need an aqualung, even sitting on the beach, as there was no oxygen in the air then. You might be a little cautious when taking a paddle in the sea, too, because one of the features of an oxygen-free world is that the ocean waters fill with dissolved iron, a little like the bitter, toxic water that sometimes gushes out of abandoned coal mines. At some time, deep in the Archean, more than three billion years ago, microbial life seems to have become involved, to begin to clear the oceans of their huge stores of iron, causing it to drift down as layers of iron oxides – rust, in effect – on the sea floor. Was this the beginning of photosynthesis, the source of the oxygen in the air today? There's a mystery here, as the first proper signs that oxygen in the air was beginning to rust the land surface was not until hundreds of millions of years later. Perhaps, some think, these microbes then used a different kind of photosynthesis, that did not then produce free oxygen. That would have been a sensible trick, if so, as the highly reactive stuff that is free oxygen would have been as dangerous to living things then as chlorine is to us today, before they evolved the molecular machinery to cope with it. It was one of the many dangers for life on a young planet.

11 (2.87 Byr)
Sedimentary rock from the Banded Iron Formation
Wyoming, USA

Ridding the early oceans of the huge amounts of dissolved iron they contained took over a billion years, and formed huge iron ore deposits, that dwarf all others. So, the car you drive in, the steel that supports the building you live in, the knives, forks and spoons you eat with – all these are very likely to have come from some of these monstrous iron strata from somewhere in the world. The Banded Iron Formations have become an integral part of Earth history. They are quite beautiful rocks too, for the bright red of the iron oxide is finely interlayered with white silica, the iron redness surviving crushing so that the layer in the Urn retains its ancient tinge. The BIFs hold some puzzles, though. For instance, although life is thought to have played a key role in transferring the iron from the ocean waters to the sea floor, it has not left much sign of itself, and many BIFs only contain scraps of carbon. Perhaps, some geologists think, the chemical processes that trapped the iron also consumed the bodies of the microbes involved.

12 (2.7 Byr)
Archaean pillow lava
Belingwe Greenstone Belt, Zimbabwe

Among the signature rocks of these Archean terrains are the greenstone belts. Here, the rocks are green because the original dark minerals that crystallised from magma have been altered by heat, pressure and percolating subterranean fluids to a distinctive greenish tinge. Many of these rocks clearly erupted as basalt lavas, similar to those that make up the ocean crust today. Some of the tell-tale signatures are there, such as the way in which the lavas take the form of piles of pillow-like structures, the 'pillow' shape being caused by sudden chilling of incandescent magma into cold seawater. But are these rocks really a fossilised fragment of an ocean floor, akin to the ones we see today? The world's greenstone belts have generated much controversy, and the more ancient ones may well have formed on an early Earth which operated too differently as a planet to speak in terms of 'continents' and 'oceans' as we understand them today. But by the time these examples formed, a 'mere' 2.7 billion years ago, modern-style plate tectonics had almost certainly been established, and so at this point, we can – most likely! – celebrate one of the first *certain* ocean floors on Earth.

13 (2.65 Byr)
Cheshire stromatolite
Belingwe Greenstone Belt, Zimbabwe

A few layers ago in the urn, we visited the first widely accepted evidence of life, as the layered microbial rock structures called stromatolites, from Australia's Strelley Pools. Now, the best part of a billion years later, we return to the history of life in Zimbabwe's Belingwe Greenstone Belt – and it is also one of layered microbial stromatolites! This seemingly endlessly monotonous fossil record of Earth's early history (of a kind, indeed, that would persist for nearly two billion more years yet) used to be taken as evidence of terribly slow evolution amongst a few dull and simple life-forms on the early Earth. Appearances here, though, are deceptive. For a start, the chemistry of these stromatolites suggests that the microbes forming them had by now learnt the trick of modern-style photosynthesis, and were beginning to release oxygen into the air. And, the flood of scientific data now emerging on the genetic make-up of organisms suggest that the great tree of life's diversity on Earth is almost overwhelmingly dominated by different groups of microbes. The spectacular multicellular plants and animals that loom so large for us humans only make up a few twigs of this mighty tree, most of which grew and diversified – quite invisibly to geologists and palaeontologists – on the early Earth of Archean times. To our perceptions, it's a world turned upside down. But, this revolution in understanding takes us closer to the underlying truth of our planet (and perhaps of other planets too).

14 (2.5 Byr)
Archean butterstone stromatolite
South Africa

Two and a half billion years ago, the Earth was on the verge of another great step in its history, to make it sharply distinct from the other planets that orbit our Sun (and, almost certainly, from most other planets of this galaxy and others). The ocean-wide microbe populations, including those of the stromatolite colonies on the sea floor, were releasing enough oxygen for this to extend from initial 'oxygen oases' into the atmosphere to begin to visibly change the whole planet, in what geologists now call the Great Oxygenation Episode. A new phenomenon was born on the land and the wide bare landscapes were, over the next tens of millions of years, to change hue from the greys and mineral greens of the Archean Eon, to the reds, oranges and browns of the Proterozoic Eon that was beginning. Much life suffered in the process, as free oxygen was deadly to most organisms then; for these it was an oxygen catastrophe. Life, though, began to evolve mechanisms to protect itself from this fiercely reactive gas – and then eventually to exploit its energy-releasing potential. In the long run, life was tightening its grip on this planet.

15 (Precambrian, precise age unknown)
The mineralogical explosion: turquoise, deep blue azurite, and brilliant green malachite; unambiguous signs of life

We often take Earth's storehouse of minerals for granted, as an unchanging part of this planet and of others, too. Indeed, we sometimes read of the visions of interplanetary prospectors, who dream of one day exploiting vast mineral riches in space. The truth of these riches, though, lies much closer to home. Go out into the great stretches of interstellar space, and you may find perhaps a dozen minerals (though these do include tiny grains of diamond). Go to where the dust thickens and melts amid the birth of a star system (as symbolised by the lowest, meteoritic layers of this urn) and that number may climb to a few hundred minerals. As Earth was born, its chemistry was stretched still further amid great ranges of heat and pressure and – helped by abundant supplies of liquid water, that great facilitator of mineral formation – the numbers of minerals climbed to a couple of thousand or so. Life produced another giant step, two and a half billion years ago, as photosynthesis filled the air with oxygen, and swathes of oxides and hydroxides appeared at the Earth's surface. By then, there were a little more than 5000 minerals on Earth – riches indeed. That, by the way, is not the end of the story, as something extraordinary is still set to happen – *much* later – to the Earth's mineral storehouse.

16 (1.8 Byr)
Pyrite rain: a black shale packed with pyrite that records the onset of the Proterozoic sulphidic ocean
Koolpin Formation, Pine Creek Geosyncline, North Western Australia

As the Archean world gave way to the Proterozoic one, changes reverberated across the planet. Many of these were to do with the rise of photosynthetic microbes, and the spread of oxygen into the atmosphere. One change was the transformation of the ocean, as the newly rusting land surface for the first time began to form oxidised sulphur compounds – sulphates – and rain and rivers washed these into the ocean. These sulphates then underwent a rather beautiful change as they drifted into the still-stagnant ocean depths. As if in some magical cartoon, they transformed into exquisite, complex crystals of iron sulphide – pyrite, that is, often known as fool's gold – and rained down on the ocean floor. The little piece of shale now ground to dust and placed in this urn will have contained thousands of them. This Proterozoic world of sulphidic oceans was generally a stable one – geologists often call it the 'boring billion'. For all that billion-year stability, though, change was still taking place in the background, and more revolutions were, eventually, to come.

17 (1.45 Byr)
Tidal varves
Northwestern Montana, USA

The Moon has been a constant companion of Earth since the cataclysmic impact of planet Theia with the proto-Earth (called planet Tellus by some) at the dawn of Hadean times, some four and a half billion years ago. But, exceedingly slowly, this relationship has become a more distant one. The Moon's orbit around the Earth has, over that time, raised the tides, day in, day out, over that vast expanse of time. The system, though, is not some kind of perpetual motion machine, set to work for eternity. The Moon is drifting farther from the Earth, at a few centimetres per year, and the Earth's spin is slowing down. The change is literally written in the rocks, for the passage of the tides, in some places, can build up layers from each successive tide, with thicker layers at spring tides and thinner ones at neap tides. The strata, millions of years later – or 1.45 billion years later as in the case of this sample, from the mid-part of the Proterozoic Eon – can be interrogated by geologists, to reconstruct how the tides flowed in those days, and how the Earth and Moon behaved then. A Proterozoic poet, as the brief days flew past (with more than 500 then each year), could contemplate the large Moon hanging overhead: it was some 5000 kilometres closer to us at that distant time.

18 (1.2 Byr)
Sedimentary rocks from the Belt Supergroup
Montana, USA

The rocks of Montana's Belt Supergroup of rock formations show the two faces of the oceans of the Proterozoic world. In those rocks that represent deep water, the oxygen-starved 'sulphidic' oceans from more than half a billion years ago persisted, where tiny pyrite crystals formed in the water and rained down to join the sediment grains. But, in the shallower waters, there was sufficient oxygen by this time to help support some of the new kinds of life that were slowly emerging among the otherwise ancient and endless microbial mats, and that were forming a new kind of fossil in these strata. Larger organisms were beginning to emerge.

19 (1.2 Byr)
Oldest multicellular fossil: *Horodyskia*
Australia

When did the first multicellular organism appear on Earth, to begin to break the grip of the microbes? When one goes fossil-hunting for the petrified remains of this pioneer, it becomes clear that this isn't a simple question. It's not just a question of size as, while most bacteria are tiny, a few are huge (for a bacterium) approaching a millimetre across. For proper multicellularity, too, one needs the right kind of cell, that has evolved a nucleus, for these can then come together to form complex structures like eyes and muscles. Seeking that kind of fine detail is hard in the fossil record. To make things still more confusing, some simple microbes can form chains, and mimic true multicellular organisms. So one prospects among the ancient rock strata for likely-looking fossils, and interprets them as best one can. One such is *Horodyskia*, more than a billion years old, and looking a little like a string of flattened beads on the rock surface. We can welcome it, cautiously, as a pioneer of multicellular life on Earth.

20 (1.2 Byr)
Green protozoa
Hopei province, China

The slow rise of more complex life midway in the Proterozoic, a billion years ago or so, did not only affect the larger, multicellular organisms that were beginning to develop at that time. Microscopic, single-celled organisms became more complex too. *Very* carefully dissolve a piece of shale of that age in strong acid, and with luck one can find the tiny skeletons of protozoans (more formally called protists these days), single-celled organisms that had nuclei, and organelles like energy-producing mitochondria and the chloroplasts that carry out photosynthesis. Unlike the very first microscopic fossils, from the dawn of life, which were mainly simple spheres, these skeletons – the hardened outer surfaces of the protozoans – were often spiky, or had trapdoor-like openings, or tile-like structures on the surface. This elaboration on the outside mirrored the greater sophistication within the cells. Life was on the move.

21 (1.2 Byr)
Torridonian sandstone
Scotland

The Torridonian sandstones of the spectacular Northwest Highlands of Scotland allow you, almost literally, to walk on landscapes a little more than a billion years old, from the days when Earth was leaving its youth and approaching middle age. These rocks have not been mangled and crumpled like most of the Earth's older rocks. Instead, they were merely once tilted by mild tectonic nudges to lie at a gentle angle – and then most conveniently re-tilted to lie flat again. The Torridonian rocks are the hardened remains of sands and gravels carried by a mighty river system from mountains rising in the east, as far as Greenland – a river journey that was possible in days before the Atlantic Ocean formed. These river deposits are in mellow rusty shades of red and brown – a sign that the atmosphere was filling with oxygen, though still at levels that would leave a time-travelling human gasping for breath. That time-traveller would have found grandeur in the scenery, though desolation too: no grass, no trees, no flowers. It wasn't completely lifeless – a sharp eye might see greenish microbial patches by damp riverbanks or in small ponds on the floodplain. *Almost* completely barren landscapes like this were to persist for another half-billion years and more, even as biological evolution began to develop prolific new patterns in the sea. The land was a tough place for life to get used to.

22 (1 Byr)
Mudstone rock surrounding first seafood fossils, *Proterocladus antiquus*
Dailan, China

A billion years ago, the land might still have been barren, but one kind of iconic life started to colonise the seas, and likely get washed up on beaches too. This was green seaweed, a multicellular green alga complete with branching fronds and roots to anchor it into the sea floor. Beautiful fossils of this oldest (so far) seaweed have been found in China, looking a little like flattened, blackened tangles of spaghetti. Such plants are sources of oxygen to water and air, and also now form the base of the food chain that supports the rest of life. A billion years ago, though, in the depths of the Proterozoic Eon, there were no fish to nibble at the seaweed, nor snails to graze on them, and so the forests of seaweed could begin to spread unhindered across the sea floor. Part of today's familiar seaside landscape was being put into place.

23 (Proterozoic, precise age unknown)
Columnar stromatolite
Torgo, Saha-yakuti, Russia

Biological revolutions were taking place in the 'boring billion' years of the Proterozoic Eon, between two and one billion years ago: the evolution of cells with nuclei, like the ones in our bodies, and their assembly to form large multicellular organisms. But these revolutions came with no fanfare, and did not transform the biosphere overnight. Microbial life, typified by bacteria, still dominated Earth. Their visible presence, as the layered 'living rocks' that are stromatolites, remained ever-present on sea floors. After all, the microbes had had two billion years, at least, to evolve a dazzling diversity (one that was hidden to us before the modern magic of genome analyses). In the course of that long evolution, they had learnt tricks that more supposedly advanced organisms like flowers and mammals still cannot do – like being able to 'breathe' using chemicals other than oxygen. And, the new multicellular organisms had tough problems to overcome, like making the cells of a completely new kind of body work together properly. Things were to change, of course – but maybe not quite so much as we might think. For instance, remove all flowers and all mammals from the Earth, and life would adjust and carry on. But remove all bacteria, and the basis of life on this planet would collapse within days. The enduring stromatolites deserve our respect.

24 (580 Myr)
Precambrian tillite
Mortensnes, Varanger Peninsula, Norway

The 'boring billion' years of the Proterozoic Eon came to a spectacular end, a little more than 700 million years ago. Climate throughout that long time had been consistently warm. But then came the most profound deep freeze in all of Earth history. It's been called Snowball Earth – a time when glaciers reached the equator and stretched, hundreds of metres thick, across the ocean. The Earth became a blindingly white ball, and its bright mirror-like surface indeed helped maintain the frigid conditions, by reflecting the Sun's warmth-giving rays. Why did it start? That is still a mystery, but some scientists point to huge flows of basalt lava on land just before it started. As these were then weathered by wind and rain, the chemical reactions involved might have sucked enough carbon dioxide out of the atmosphere to weaken its greenhouse effect, sufficiently to kick-start the ice advance. The end was a reverse of this process, and catastrophically rapid. Volcanoes continued to erupt through the ice, belching carbon dioxide into the air until its greenhouse warming effect overcame the mirror effect of the ice. As temperatures soared, the worldwide glaciers quickly broke up, amid floods of meltwater. Dramatic times, indeed – and ones that still hold a lesson for us today.

25 (570 Myr)
Ediacaran biota: Woodhouse Beds in which *Charnia* was found
Charnwood Forest, UK

The fierce, extraordinary Snowball Earth glaciations that brought the 'boring' times of the Proterozoic Eon to an abrupt end and encased our planet in ice should, one might think, have been catastrophic to life. Yet, a few million years after the ice had tumultuously receded, the first proper community of large multicellular animals appeared on Earth. These are now called the 'Ediacaran biota' after the Ediacara Hills in Australia, where beautiful fossils of these forms occur, but they were first found in the rocks of Charnwood Forest, in Leicestershire, UK. Even after a half-century of intense study, they remain enigmatic, and geologists are uncertain whether they are closely related to later, more familiar animals, or whether they were something quite unique – an early, and ultimately failed, experiment in large life-forms. Looking like fronds, or discs, or with yet more puzzling shapes, they sat anchored in the seabed. Lacking an obvious mouth or gut, they seem to have absorbed nutrients from the sea water. Scarcely being able to move, there were neither hunters nor prey among them. For fifty million years, they lived peacefully on Earth. It was a kind of Garden of Eden. But, it was not to last.

26 (635-541 Myr)
Clues to microbial mats in the rocks
Russia

It is almost time to bid farewell to the longest empire the Earth has ever known: that of the near-endless sea floor microbial mats that stretched across from ocean to ocean, and through the Archean and Proterozoic Eons – a span of some three billion years. They are most obviously seen in the stromatolites, those mounds of layered sediment quickly hardened into something like ready-mix concrete by the chemistry of the microbes. But softer, sticky microbial skins extended far more widely across soft sands and muds. Too soft to fossilise easily, they nevertheless left their marks in the sediment by the way they held the mineral grains together. When a current flowed above such mat-bound sediment, it ruffled the sea floor into wrinkles, or textures that look like elephant skin – and it is these markings that can persist in strata. They are postcards from a different kind of planet.

27 (550 Myr)
First muscles: unknown animal burrow
Namibia, Africa

550 million years ago, at the very end of nearly two-billion-year-long Proterozoic Eon, the biological revolution, that had been slowly burning its way through the last billion years of that eon, began to explode. When that explosion finished, a mere thirty million years later, the world was transformed from one dominated by microbes, to one in which large animals flourished in the seas. A key innovation here was muscles – and so the ability for animals to move under their own steam. These first muscles (and the animals that grew them) left few fossils of themselves – but their actions left striking signals in the rocks. These wormlike animals slithered and burrowed across and through the sea floor, churning the sediment and ripping up – and often chewing through – the microbial mats that had held sway for so long. From now on, seafloor sediments were to be thoroughly mixed by these energetic, muscular invaders, to make a new habitat for the life to come.

28 (547 Myr)
The first true skeletons: sediment surrounding *Cloudina carinata*
Driedoornvlakte, Rietoog, Hardap Region, Namibia

When animals first started to move, they also found a new target: other animals, that they could kill and eat. Those prey animals had to find means of defence, by wriggling faster – or by growing a suit of armour. The first skeleton to appear on Earth did not look terribly impressive, being the hard tube-like cones of *Cloudina*, little bigger than a matchstick. Nevertheless, for all their makeshift structure, they clearly served their purpose, for *Cloudina* is relatively common in rock strata of latest Proterozoic age. Look closely at these skeletons, and one can often see little drilled holes, made by some unknown predator. Some of these holes go right the way through this external armour, to signal that *Cloudina* individual's demise. But others do not penetrate all the way through this external skeleton, meaning that *Cloudina* survived that attack, and lived to bear witness to its tale. That was the start of an arms race between hunter and hunted, that goes on to this day.

CAMBRIAN
539-487 Myr

29 (518 Myr)
Heliomedusa, Chengjiang brachiopod
Yu-Anshan Formation, China

The Cambrian Period, of half a billion years ago, is when complex, multicellular life exploded into all the main groups of animals we know today. By one of those fortunate quirks of geology, Cambrian rocks are also unusually rich in fossil localities which preserve not only shell and bone – the usual materials that are fossilised – but also soft tissues such as skin, eyes, guts and nerves. These extraordinary localities give us windows into the past, illuminating the biological communities that lived then. One celebrated set of rocks here are the Chengjiang strata of China, that have yielded a spectacular array of fossil organisms including worms, jellyfish and delicate crustaceans, preserved in red iron oxides that contrast beautifully with the pale shale surfaces. The Chengiang fossil consigned here to this urn is the brachiopod (or 'lamp-shell') *Heliomedusa*. As well as the shell, it preserves the fringed tentacles with which it filtered food particles, and harvested oxygen, from the Cambrian seawater, and the fine bristles with which it sensed the movement of other animals. Looking at such fossils, one could be forgiven for thinking they died yesterday.

30 (515 Myr)
Girvanella, oncolite, blue-green algae
Marble Mountains, California, USA

Lest one was to think that the Cambrian Period was the preserve of fossil animals – although it was the time of the greatest burst of evolution in their history – we can introduce here *Girvanella*, a calcium carbonate-secreting alga of that time. Although the particular specimen that graces this urn hails from California, the name comes from closer to the artist's home, after the Scottish town of Girvan, where some fine specimens were discovered and named almost a century and a half ago. The fossil itself is simple – just a set of small calcareous tubes – and like many simple fossils it caused a good deal of head-scratching among the geologists studying it. Indeed, it was first assigned to the animal kingdom, to amoeba-like protozoans called foraminifera, which can build elaborate skeletons out of calcium carbonate. But, *Girvanella* was then reassigned to the algae, and its remains were later discovered in rocks of a whole range of ages, up to the times of the dinosaurs. Indeed, there are similar algae living today, so one might – only a little optimistically – look upon it as a living fossil.

31 (510 Myr)
Small shelly fossils
Lower Cambrian Forteau Formation, Newfoundland, Canada

It seems a ludicrously vague term for palaeontologists, who have a reputation as the most precise of people. 'Small shelly fossils' can mean almost anything, surely? Nevertheless, the term has stuck, and even acquired an acronym – SSFs – among the palaeontologists who work on that great transformation that was taking place around the beginning of the Cambrian Period, which is simultaneously the beginning of the Palaeozoic Era and the yet grander Phanerozoic Eon (we still live in the last of these, 542 million years after it began). Dissolve a piece of early Cambrian limestone in acid, and hundreds of small spiky objects are likely to tumble out: squares, disks, spikes, and yet more baroque objects. These are all parts of the skeletal armour of early animals, many of which remain quite mysterious, even when complete specimens of them are found. Take the chancelloriids, for instance, basically bags covered with spikes, or the bizarre *Wiwaxia*, like some punk undersea hedgehog. No-one is quite sure what kinds of animals these were, even though their spiky remains have been much pondered on. The mysteries of the Cambrian Explosion, when all the main animal groups appeared in a mere 30 million years, will take some time to unravel yet.

32 (510 Myr)
First reef on earth: archaeocyathid
Newfoundland, Canada

The Cambrian world brought with it a pattern of life that was to persist, on and off, throughout the following half-billion years: that of the reef. It's a word with many connotations. To a mariner, it's a perilous stretch of wave-lashed rocks along a coastline, where lives are risked and all too often lost. To a marine biologist, it's a paradise of biological diversity, epitomised by the classic coral island. A geologist's view combines both perspectives: as a biological reef grows over time, it typically produces a mountain of rock, the calcareous skeletons of countless reef organisms piling high in masses that can reach kilometres in thickness. It is the rough tips of these undersea mountains that today threaten ships and sailors' lives. Over the half-billion years of the Phanerozoic Era, there have been times when reefs have flourished, and times when they crashed out of existence, disappearing for millions of years. With each reappearance, they came back in different biological patterns. Today, reefs are dominated by corals and hard coralline algae, which form the framework and shelter for the rest of the rich ecosystem. The first 'proper' reefs of all, in the early Cambrian Period, were largely built of cone-shaped organisms called archaeocyathids. Probably related to sponges, they flourished for just a few million years before they, and the reefs they formed, disappeared. The archaeocyathids never came back – though reefs eventually did, as new reef-builders evolved millions of years later. As today's reefs increasingly suffer from global warming, it's a timescale of recovery to bear in mind.

33 (510 Myr)
Cephalon of the trilobite *Olenellus thompsoni*
Pennsylvania, USA

A few million years into the 'Cambrian explosion' of multicellular life, there appeared the animals that are the poster children for the Cambrian Period – and indeed for pretty much the whole of that larger time unit that the Cambrian forms the beginning of, the Palaeozoic Era, that spanned nearly 300 million years. The petrified remains of their lustrous tri-lobed, multi-segmented carapaces characterise the Palaeozoic, just as the dinosaurs symbolise the succeeding Mesozoic Era. Trilobites have been venerated by native American Indian tribes, adopted into municipal English coats of arms – and even cast as the villains in a Hollywood horror movie. Their origin, though, is something of a mystery: two different groups of trilobites appear, at more or less the same time, on two separate continents of the early Cambrian Earth. So, somewhere out there is the ancestor of all trilobites, and maybe palaeontologists will find it one day. The trilobite that has been ground to powder for this layer of the urn, *Olenellus thompsoni*, is as handsome as any of its kin, with a large head, and fearsome-looking spines coming out of its body and tail. It would have inspired fear, certainly, among its smaller prey on the Cambrian sea floor, as the struggle between the hunters and the hunted of this world was beginning.

34 (508 Myr)
Margaretia dorus, enigmatic organism
Utah, USA

The Burgess Shale of British Columbia is one of the classic Cambrian fossil localities that, like China's Chengjiang strata, preserves a wealth of soft-bodied animals and tissues, a window into the full exuberance of marine life of those days. Many of the fossilised animals are at least broadly familiar, but some are strange, and puzzling. One of the puzzles lies in this layer: *Margaretia dorus*, a curious organism that has changed its identity in more ways than one. Looking like a set of frond-like, flattened tubes, it was originally classified as a soft coral, and then as a green alga – a kind of seaweed, in other words. A yet closer examination of it suggested that these tubes were in fact structures built by a kind of worm (an acorn worm), the soft remains of which have been found in the Burgess Shale and called *Oesia disjuncta*. So *Margaretia* is really *Oesia* (or rather the house that *Oesia* lived in). It is the kind of merry-go-round of concepts and names which is not unusual in palaeontology and – who knows? – this one may have another turn or two in it yet.

35 (505 Myr)
Ellipsocephalus hoffi, trilobite
Jince, Bohemia

The trilobites that flourished in the Cambrian Period lived only in the sea (as, indeed, did most of life then). But within the ocean, their realm extended from shorelines to the deep ocean, and clues to their habitat and mode of life can often be gleaned from the shape of the carapace that was their skeleton. The finely powdered trilobite preserved here, *Ellipsocephalus hoffi*, was small and blind, like many cave-dwelling animals today. It is thought to have grubbed about in the mud of a deep, dark sea, and moreover a deep sea that was often starved of oxygen – so an environment that was off-putting to any large active energy-hungry predator. These poorly oxygenated deep ocean waters would remain an important part of Earth's environment for many millions of years to come, and so would continue to form a haven for the animals that could adapt to their rigours.

36 (500 Myr)
Palaeacmaea irvingi, soft-bodied organism
Wisconsin, USA

Another of the Cambrian's mysteries is *Palaeacmaea*, only found in those special Cambrian fossil localities that preserve soft tissues, and not just bones and shells. It looks on the rock surface a little like a child's toy – a low cone decorated with concentric rings. Since that doesn't provide many clues to biological identity, it has been interpreted in different ways by the different scientists who have studied it. It was originally thought to be a snail, one something after the manner of a limpet, and then it was reclassified as a monoplacophoran (another limpet-shaped kind of mollusc, now rare as a 'living fossil' but common in Palaeozoic times). But *Palaeacmaea* didn't have a hard shell, and very close examination showed that the cone shape had been flexible, not rigid, in life. So, it was then recategorised again – most tentatively! – as something quite different, a kind of jellyfish. There will doubtless be more interpretations to come.

37 (496 Myr)
First eyes to see: trilobite *Olenellus truncatus*
Sweden

The gift of sight is so important to an active, mobile organism – whether one that hunts or one that is hunted – that it has been evolved independently many times in different groups of animals. Perhaps the first animals to develop this sense, early in the Cambrian Period, were the trilobites, whose remains form the most iconic of fossils of those times. Trilobite eyes are extraordinary – and extraordinarily beautiful when looked at in detail. They are nothing like our own eyes, but a development of their protective armour, transformed into exquisite arrays of lenses, rather like those of a fly. The light-catching crystals within them are sometimes so finely preserved that one can – with a bit of technical help – literally see through the eyes of a trilobite. The eyes of the *Olenellus* in this layer are typical of those of trilobites, with one on each side of the head, each on a tilted curved platform to look upwards, sideways and outwards – as befits a sea floor animal that has to watch for both prey and predators that may be at the same level, or approaching from above. Later trilobites developed this sense yet more acutely – including some that swim high in the plankton, where the eyes went all around the head to give all-round vision.

38 (ca 493 Myr)
Annelid worm trail, Red Rock fossil
Trawsfynydd, Wales

The extraordinary array of animals that burst out upon planet Earth in the Cambrian gave rise to a new kind of fossil – the trace fossil. These are not the remains of body parts but rather tracks, trails, footprints, burrows and all of the kinds of impressions of animal movement that may be impressed on or in a layer of soft sediment, and then be buried and petrified quickly enough to persist in the strata for many millions of years. The trace fossil in this urn layer is one commonly found in rocks that extend from the Cambrian and right up to the present: that of some worm-like animal moving along the sea floor. The immortality of this unknown animal was likely hard-won. Many such trails are preserved through sudden burial by a fast-moving submarine 'avalanche' of muddy sediment, termed a turbidity current, that typically smothers all the animals in its path. If the suddenly dumped sediment layer is not too thick, though, some animals can fight their way back to the surface. Their salvation can be petrified in that stratum, too, as an escape trace.

ORDOVICIAN
487-443 MYR

39 (480 Myr)
Dendroid graptolite
Fezouata Formation, Zagora area, Morocco

Can an elephant really learn to dance? Something akin to this happened at the very beginning of the Ordovician Period, about 487 million years ago, when some rather obscure seafloor animals literally took a leap into the unknown. These were the dendroid graptolites, small cone-shaped colonial animals that had appeared in the preceding Cambrian Period and, together with the sponges and corals and the briefly successful archaeocyathids that we met previously, set up shop to make a living. All these animals rooted themselves into the sea floor and fed by filtering minute food particles out of the seawater. Then, that extraordinary leap. Some dendroids abandoned the sea floor, to become an impromptu part of the plankton, drifting high above. It should have been a calamity for these pioneers, as they were absurdly maladapted for such a different lifestyle. But, somehow they survived – and thrived and multiplied; these new oceanic pastures were then filled with nutrients but had few predators (no oceangoing fish, yet). The fossilised remains of these planktonic dendroids – looking, indeed, a little like tiny ballerina dresses on the rock surfaces – are one of the main signals to a geologist that they have encountered these earliest Ordovician strata. To adapt themselves better to their new lifestyle, they would, as the planktonic graptolites, over the next hundred million years, go on to indulge in one of the fastest and most furious bouts of evolution known to palaeontologists.

40 (475 Myr)
Tetragraptus fruticosus, *Phyllogratus typus*, graptolites
Victoria, Australia

Just a brief few million years after the graptolites burst into the plankton these extraordinary colonial animals had changed utterly. From each colony being made of hundreds of branches and thousands of individuals, as with the original pioneers, the colonies were now typically reduced to just two or four branches, each with just a few tens of individuals. These smaller, sleeker constructions were now much better shaped to ride the ocean currents, and to harvest food particles from them. What is yet more intriguing is a new realisation that the fossil remains of the graptolites are not skeletons in the usual sense, as are bones or shells. Rather, they were 'homes', co-operatively *built* by these tiny creatures. Like nest-building wasps or termites, the graptolites were animal architects – a skill, therefore, that goes back to the dawn of complex life.

41 (470 Myr)
Hoekaspis megacantha, trilobite
Bolivia, South America

The trilobites, those most charismatic of carapace-bearing animals, may not have been quite as dominant as in their heyday in the preceding Cambrian Period, but they were still a hugely important part of the marine ecosystem of early Ordovician times. It is too early to speak of a decline of the trilobites. Indeed, they were beginning to be caught up in a general expansion of ocean life which was to go on throughout almost all of the Ordovician. It is almost as if this new, multicellular biosphere had been going through a kind of experimental trial run in the Cambrian, with booms and busts of different groups at different times, before increasing steadily in diversity in what became called the Great Ordovician Biodiversification Event. In this 'event' (which went on for more than thirty million years, and had its own intricate and complex history) the number of families of marine living organisms more or less tripled. That small part of it represented here was just the beginning.

42 (Ordovician, precise age uncertain)
Skolithos, worm burrow
Sweden

One of the spin-offs from the general expansion of life in the Ordovician Period was an increase in the amount of crawling over and burrowing through the sea floor, as the new life-forms energetically found new living space within the marine environment. One of the common kinds of burrows was the one that now lies within this urn layer – *Skolithos*. It is very simple – just a vertical tube made within a sand layer, and filled with sand. Sandstone layers with many *Skolithus* burrows are commonly called 'pipe rock' because the rock appears to be packed with vertical pipes. It marks a very distinct kind of environment: unstable conditions, as on many coastlines, where waves and currents are continually dumping sand on the surface of a beach or tidal flat or washing it away. The animals living in the sand – often different kinds of marine worm – have to constantly adjust by digging downwards or burrowing upwards, and *Skolithus* is the result. It is age-old behaviour, starting in the Cambrian and going right through to the present. *Skolithus* is likely forming by some shoreline near you right now.

43 (Ordovician, precise age uncertain)
Brachiopod
Utah, USA

Go to the seaside today, and the seashells washed in by the waves will almost all be of different kinds of molluscs, mostly various clams. Time-travel to an Ordovician beach, though, and the seashells will look similar at first glance, as two-valved shells joined at a kind of hinge which allows them to open or close – but they will be of a very different animal group. These are the brachiopods (which used to be called 'lamp-shells' in the days when people used oil-lamps for light). They are related to the molluscs, but very distantly, and dominated this 'two-valved' lifestyle not only in the Ordovician Period, but pretty much throughout the entire Palaeozoic Era. There are still a few kinds of brachiopod alive today, but they are generally rare. In the Ordovician, they were ten a penny.

44 (Ordovician, precise age uncertain)
Fossil rain
Scotland

Sediment layers can be like the most sensitive kinds of canvas, ready to receive and preserve impressions of the outside world. If a layer of wet mud – on a lake shore, say – is just the right consistency it can receive impressions from the tiny skittering feet of insects or crustaceans or – as in the case of this layer of the urn – the drops of a passing rain shower. Then, if that layer is quickly buried by more mud (or even better, if it dries and hardens in the Sun before burial) it might preserve a record of those few minutes of rain for many millions of years to come. Such records of rain events can help in the reconstruction of the climate in ancient times. Even more subtly – and this needs a good deal of careful measurement and calculation – it can give information on the density of the atmosphere at the time of the rainfall. That tells us something about the nature of mud, but rather more about the world as a whole.

45 (461 Myr)
Trinucleus acutofinalis, trilobite
Shropshire, England

As global biodiversity was going through its long boom throughout pretty well all of the Ordovician Period, new groups of animals appeared and took centre stage. The trilobites, those eon-symbolising fossils, were caught up in this evolutionary expansion of life, and produced some of the most characteristic forms of that time. Perhaps the most singular of them were the trinucleid trilobites. These were quite small and dwarfed by some of their dinner plate-sized kin. They were blind, too, and lived in deep, poorly lit waters. But they are instantly recognisable in having a prominent fringe that encircled all of the head of the animal, which was ornamented by a complex pattern of holes and grooves – almost like a form of Ordovician hieroglyphics. The function of this grooved/pitted fringe remains an enigma. Was it a device to help feeding in some way? Was it a sense organ to detect vibrations? The jury is still out on this question, so it is one more mystery within this urn.

46 (Ordovician, precise age uncertain)
Nautiloid
Hunan Province, China

In the Ordovician Period, the great group of animals that makes up the molluscs was meagre in some respects – that scarcity of bi-valved representatives that we encountered a few urn layers below, for instance. But in some other respects the molluscs were gearing up for dominance to come. Among these, the nautiloids took a starring role, not least for their impressive size (some of them could grow to as much as five metres long, though most were smaller). Add to that a pair of large eyes, a sharp beak, many tentacles (for these were relatives of today's squids and octopi) and possibly a considerable intelligence (for squids and octopi are nobody's fools in the animal kingdom) and all this adds up to a formidable predator. Even the largest trilobites (approaching a metre long) would want to keep clear of such a beast. Most of the length of a nautiloid was a long, straight conical shell, with the body, head and tentacles crammed into one end of it. The rest of the shell would have been a kind of buoyancy device, gas-filled so the animal could maintain its position above the sea floor as it swam. It was clearly an effective combination, if ungainly – for swimming while being attached to the equivalent of a long drainpipe seems not an ideal biological design solution. The nautiloids were eventually to give rise, though, to a neater (and even more successful) kind of engineering, as we shall see in future layers of the urn.

47 (Ordovician, precise age uncertain)
Winged brachiopod
Wyoming, USA

The brachiopods, those bi-valved shells that played such a prominent role on the Ordovician sea floor, took different shapes, adapted to their different lifestyles. This in part related to what lay *below* the shell surface, in the animal's interior. This is where the most elegant part of the skeleton often lies, as a complex set of struts which makes up a framework for the array of soft hairs with which the animal filtered food particles from the seawater. In winged-shell brachiopods, the elegant 'wings' on each side are not some device to help the animal swim (for they were firmly attached to the sea floor by the brachiopod equivalent of a hawser) but typically they gave extra internal space for a spirally coiled internal framework for more effective seawater-filtering. Such brachiopods had evolved a way to feed not only effectively, but beautifully too.

48 (455 Myr)
Astraspis and *Eryptichius*, early fish
Colorado, USA

As those assiduous 19th-century geologists were hammering a history of the Earth from the rock strata, some of the major features of biological history seemed to stand out clearly. One of these was that the rise of fish took place in the Devonian Period, from some 400 million years ago, in the rocks of which the fossils of primitive armoured fish can abound. So it was a shock when, late in that century, fragments of armoured fish turned up in Colorado, in sandstones of mid-Ordovician age, which we now know to be more than 50 million years earlier. This find was undoubted, as this fish armour is quite distinctive: with dentine and enamel layers, it is as though the animals were encased in a kind of all-round tooth. It later turned out that fish evolved even earlier, in the Cambrian Period, but they remained rare and elusive for more than a hundred million years before blossoming into abundance. The vertebrates as a whole might have ultimately given rise to dinosaurs, mammoths and humans as well as fish, but it has been probably the slowest-burning success story in all of biological evolution.

49 (Ordovician, precise age uncertain)
Hormotoma, gastropod
Kishwaukee Valley, Illinois, USA

Some parts of the Ordovician ecosystem would look strikingly familiar to a time-travelling visitor to that period, one which is separated from our own time by almost half a billion years. Take that group of molluscs that are the gastropods, for instance, more commonly known as snails: marine ones, of course, as at that time gastropods did not venture onto land, and nor did pretty much any other kind of animal. A handful of Ordovician gastropods would look remarkably similar to those that you might pick up on a beach today: the gastropod animal typically lived in a shell that was coiled into anything from an almost-flat spiral to a high spire. The gastropod that lies, in very small pieces, in this layer of the urn, *Hormotoma*, is one of the high-spire ones, and you could probably fit a couple of dozen specimens into the palm of your hand. As with gastropods today, it would have possessed the multi-functional organ that is unique to molluscs, the radula: a kind of tongue studded with minute sharp teeth, it is used to great effect by gastropods which feed both on plants and on animals (including to prey on other gastropods). The gastropod design is one that worked well from the beginning, and has never gone out of fashion.

50 (Ordovician, precise age uncertain)
Starfish
Sahara, North Africa

The animals that are clustered together within the group we call the echinoderms – which include the sea urchins, starfish, sea cucumbers and crinoids ('sea lilies') – had appeared, with all the other main groups, in that biological outburst called the 'Cambrian explosion'. By Ordovician times, echinoderms were well established. It is a very specific group of animals, not to say somewhat bizarre. Its calcium carbonate skeleton looks external, but is actually internal, like ours (there is a thin skin covering it). And, uniquely among animal groups, it has five-fold symmetry. As the echinoderms first emerged, they went through an experimental phase that evolved some animals that to our eyes are *very* bizarre, where the five-fold symmetry was mercilessly stretched and twisted. But the Ordovician included also starfish so classically star-shaped that they could figure in a child's storybook, where the five-fold symmetry shines through clearly. That storybook, though, is unlikely to mention some of the other features of a starfish, such as the extraordinary, hydraulically powered tube-feet these animals possess, that will allow them to grip a clam, prise it open and insert its stomach inside it to eat it. These are dark powers, and powerful ones. The starfish are still going strong today.

51 (450-443 Myr)
Stromatoporoid, sponge
Anticosti Island, Canada

After the demise of the reefs built by the short-lived archaeocyathids in the Cambrian, these life-built mountains of undersea rock reappeared in the Ordovician and changed their spots once more. At first the calcium carbonate used to build them was mainly produced by microbes, thus harking back to the patterns of Precambrian time. Then, other organisms began to help in the construction. Corals began to get involved, but these were generally not such prolific rock-makers then as were some other animals, that included the still-living bryozoa (or 'moss animals' – you can often see them encrusting seaweed when you are at the seaside) and the stromatoporoids, which are extinct. The stromatoporoids have been something of an enigma. Often looking rather like mounds of lasagne sheets (albeit finely sculptured ones), they were originally thought to have been some kind of coral, while now they are generally thought to have been related to the sponges. Under whichever label, they were formidable reef-builders, and established symbiotic partnerships with other organisms, such as corals and worms. The complex ecological webs of modern reefs clearly had forerunners in Ordovician times.

52 (Ordovician, precise age uncertain)
Dalmanitina, trilobite
Morocco, North Africa

It is almost impossible to grasp the sheer scale of the trilobite order, in its long history of evolution during the Palaeozoic Era. Something like 25,000 species have been described, belonging to some 5000 genera. It is a lifetime's study to grasp even a part of this diversity, which has been meticulously described in countless technical papers and monographs, the weight of this literature growing each year. A member of just one of these genera now lies scattered within this layer of the urn: *Dalmanitina*, which was common in late Ordovician times. It also had a presence worldwide, its fossilised remains having been found in Europe, both North and South America, Africa and Australia, in rock strata that represented both coastal and also deeper waters. It was something of a generalist – a generalist predator, that is, with its streamlined shape and large, well-developed eyes. It was clearly at home in the Ordovician seas – and now, its elegant remains are a prime attraction in many a fossil collection.

53 (450 Myr)
Great Ordovician Biodiversity Event: mudstones of the *Dicranograptus clingani* Biozone
Hartfell Spa near Moffat, Scotland

Towards the end of the Ordovician Period, the world seemed set fair for life. Life in the oceans had reached a peak of diversity that it was to scarcely surpass for more than three hundred million years. The climate for tens of millions of years had fluctuated but was generally globally warm. Among the signature animals of that boomtime were the graptolites, those extraordinary colonies and animal architects of the plankton that we encountered earlier, as their whirlwind evolutionary journey was beginning. By now, their submarine homes (blocks of flats, rather, given their colonial nature), that we now find as fossils, had developed a bewildering variety of shapes. Some were straight and simple, others V-shaped or Y-shaped, others elegantly spiralled, some multi-branched, yet others with spiked exteriors or meshwork walls, recalling some of the more fantastical Gaudi sculptures. Their outward complexity mirroring their hydrodynamic sophistication, they gracefully swam the ocean waters in search of microplankton to feed on. Like all beautiful creatures, they retain an aura of mystery, for palaeontologists have yet to find the bodies of the animals themselves – almost impossibly soft and delicate, they simply seem not to have fossilised. But this long idyll was, alas, doomed.

SILURIAN
443-419 MYR

54 (443 Myr)
Earliest Silurian (post-extinction) mudstones with graptolites of the *Akidograptus ascensus* Biozone
Dobb's Linn, near Moffat, Scotland

In the previous layer, we left the graptolites, those extraordinary, architecturally gifted plankton, in fine fettle, thriving in the late Ordovician seas. We tiptoe back a couple of million years, and disaster has struck – for them, and for much of the rest of complex life in the sea (most microbes, we suspect, sailed through the catastrophe with aplomb). In this intervening time, a short but cruelly sharp glaciation had taken place, with huge icesheets building on South America and South Africa (then over the South Pole). In growing, these icesheets took so much water out of the oceans, that many of the world's shelf seas – the major cradle of marine life – were left high and dry. Sediment masses perched on their edge slid and flowed into the deep ocean waters. A million or so years later, the glaciation collapsed in floods of meltwater, and oxygen-starved water swept back over the continental shelves. These shocks to the Earth System dislocated the biosphere, bringing the tens of millions of years of the Great Ordovician Biodiversification Event (and the Ordovician Period itself) to an abrupt end, in the first of the 'Big Five' mass extinction events of our eon. The effects rippled out into the plankton, where graptolite populations crashed, being reduced to a handful of species. In this layer, the first graptolites of the Silurian Period are just beginning to evolve from the survivors. They, and the rest of life, would see glory days again – but the recovery would take millions of years.

55 (Silurian, precise age uncertain)
Sea Floor: brachiopod, rugose coral, and crinoid stem
Sweden

Once the wounds left by the catastrophic end-Ordovician mass extinction event had healed, the marine ecosystems of the Silurian developed into new patterns, which have become classics of geology because of the rich fossil record that they have left. This was a world where the corals (albeit of kinds unlike those of today) spread across shallow sea floors, together with many kinds of those 'lamp-shells', the brachiopods, and the elegant crinoids or 'sea-lilies' that used their many frond-like arms to sweep microplankton from the seawater. It was a new kind of idyll – but emphatically a *marine* idyll, juxtaposed with landmasses that were still largely bare and barren. Life, for billions of years, had held fast to the security of its oceanic cradle. The invasion of the land, though, was, finally, about to begin.

56 (431 Myr)
Desmograptus micronematoides
Graptolite, New York, USA

High above, in the ocean waters, the graptolites of the plankton had been evolving at breakneck speed, producing successive, bewildering arrays of geometrical shapes, as they fine-tuned their feeding strategies and hydrodynamic sophistication. Geologists now use their rapidly changing fossilised remains as one of the supreme age-dating mechanisms in geology, a classic of biological evolution put to the most pragmatic of uses. But, far down below, the branch of the graptolite family that had stayed rooted to the sea floor carried on in much the same way as it had done since those early days in the Cambrian. These broadly conical, many-branched colonies, like the *Desmograptus micronematoides* in this layer, have a different lesson for us: that, once a successful formula is found, it can keep going for many millions of years – and even sometimes outlast its more adventurous kin (for these sea floor-dwelling forms were to persist long after the planktonic species had perished).

57 (427 Myr)
Cooksonia, the first true land plant
Much Wenlock valley, Shropshire, England

For over a hundred million years after the 'Cambrian explosion' of complex multicellular life, the seas teemed with trilobites, corals, brachiopods, and the many other organisms that made up the rich early Palaeozoic ecosystems. Throughout all of that time, the land was largely barren. It was a domain thoroughly hostile to life that had been incubated in seas that were warm, stable, and supportive. On land, there was always the threat of drying out, and even where there was water, in rivers and lakes, its chemistry (or lack of it) was alien and toxic to salt-water creatures. Temperature swings on land – just between day and night, for instance – were far greater than in the sea, the dangers of frost or sunburn were ever-present, while the simple force of gravity, once out of water, was cruelly felt. Life on land was most definitely a challenge, and the first steps to serious colonisation only took place in the Silurian Period. Foremost among the pioneers was the land plant *Cooksonia*. Its modest appearance entirely belied the giant evolutionary step it had taken: it was simply a green stem that branched a few times, tendrils that anchored it in the ground, and a few spore-cases, the whole being ankle-high to any time-travelling human. Undramatic as *Cooksonia* was, it literally laid the ground for the invasion that was to come.

58 (Silurian, precise age uncertain)
Trilobite
Virginia, USA

The trilobites were struck amidships by the catastrophic end-Ordovician mass extinction. Some of the varieties that had flourished in the Ordovician vanished from the seas. The victims included those enigmatic blind, fringe-bearing trinucleid trilobites – and also their polar opposites, planktonic trilobites with huge, all-seeing eyes that wrapped all the way around the head. These kinds of trilobites disappeared, and their like never came back. The group as a whole survived, though, and in the Silurian other forms of trilobite scuttled across the seafloor – albeit in diminishing numbers. These animals were, very slowly, losing the evolutionary arms race, not least as newer, larger, and scarier forms of predator were coming on to the stage. How could a poor trilobite defend itself in an increasingly cruel world? From the beginning, trilobites had the useful trick of being able to roll up when danger threatened, to protect their soft undersides. Some Silurian trilobites grew long spikes too, perhaps as additional deterrence to would-be trilobite-eaters. Hedgehog-style behaviour, it seems, goes back a *very* long way.

59 (425 Myr)
Coral *Heliolites* sp.
Lickershamn, Gotland, Sweden

The coral specimen interred here is a tiny fragment of a huge development that took place in the Silurian Period on a shallow sea floor of what is now Gotland, in Sweden (and that, petrified and exhumed, forms the spectacular limestone landscape of the Gotland coast today, including the precipitous *rauks*, local versions of sea stacks). As part of the slow biological recovery after the catastrophic end-Ordovician mass extinction event, reefs – devastated in that event – were beginning to grow once more, and for the first time corals played a major role. These corals were rather distantly related to today's corals (they were built of a different calcium carbonate mineral, for instance) but they seem to have evolved the same strategy that today's corals use: sheltering algae within their tissues in a symbiotic relationship, so that these corals in effect became photosynthetic, to supercharge their growth. The Gotland fossil coral colonies, like the *Heliolites* here, were often shaped like thick pancakes, that carpeted the sea floor – likely an adaptation to catch as much sunlight as possible. And so the hyper-diverse reef ecosystems began to spread around the world once more.

60 (424 Myr)
Beyrichia, ostracod (seed shrimp)
Ludford Lane, Ludlow

For a fossil to be small is usually a sure route to palaeontological anonymity, and ostracods (or seed shrimps in the vernacular) certainly get nowhere near the popular attention that the dinosaurs do, or – going down the scale a little – the trilobites. That neglect, in this case, is entirely unjust. The ostracods, since their appearance in Ordovician times, have persisted right to the present day (there are probably some happily living in a pond near to you, right now), outliving both the (non-avian) dinosaurs and the trilobites, and generally sailing through the mass extinction events of the last half-billion years. Among multicellular animals, they are in the front rank of contenders for the accolade of ultimate survivor. They don't look like much from the outside, resembling somewhat lumpy rice grains. That exterior is a paired shell-like structure, while inside is a tiny shrimp-like animal with jointed legs and antennae, which poke out while the shell is open. It's a marvellous formula for getting by in the sea, in freshwater, and even on land. This particular specimen, *Beyrichia*, is from a sandstone that represented a coastal area with strong storm currents and salinity changes: a tough environment for most marine organisms, but *Beyrichia* thrived. If the planetary scientists ever find complex life beyond Earth, it probably won't drive a flying saucer or be Dalek-shaped: much more likely, it will look like an ostracod.

61 (424 Myr)
Thelodus sp., armoured fish scales
Ludford Lane, Ludlow

As marine life evolved prodigiously, from Cambrian through Ordovician then Silurian times, into a cornucopia of trilobites, molluscs, brachiopods, corals and suchlike, there was one ghost at the feast. Fish, those earliest forms of vertebrate life, had appeared way back in the early part of the Cambrian – but then stayed vanishingly rare for the next hundred million years (we encountered one of their rare Ordovician appearances some time ago in the urn). Mostly clad with heavy external armour, they generally seem to have clung to unstable shifting coastlines, perhaps because few of their predators ventured there. Late in the Silurian, though, their fossil record begins in earnest: they were breaking through, both in the sea and in freshwater. This layer, the Ludlow Bone Bed, is one the signposts to this long-delayed success. Little more than an inch thick, and looking like gingerbread, it is packed with the tiny fossilised scales of early fish – mainly thelodonts, which in life looked a little like small (and not very posh) shopping bags covered in little studs (and so quite the opposite of the streamlined appearance we associate with fish today). Why so many dead fish in one layer? It used to be thought to be the result of some catastrophe, but more likely these heavy scales were simply swept together, post-mortem, by some freak of waves and tides on a shoreline. Whichever story is true, this was a marker: the fish had arrived, in shoals.

62 (Silurian, precise age uncertain)
Nautiloid
Poland

The nautiloids – those predators that look as though they have evolved specifically to star in underwater horror films, complete with tentacles, ferocious beak and mobile chimney-shaped shell – thrived in the Silurian Period, and the remains of those impressive shells are commonly found by fossil-hunters in strata of that age. Only here, there are signs of evolution towards a more hydrodynamically sensible – if somewhat less melodramatic – shape. The shell is now often gracefully curved rather than typically ramrod-straight as it was in Ordovician times. These were marvels of biological engineering, as the many chambers of the shell were filled with gas from a special blood vessel (you can see its course in the fossils, if you have a nice specimen and examine it carefully) to allow the animal to adjust its buoyancy to exactly suit that of the seawater around it.

63 (Silurian, precise age uncertain)
Red Horn Coral
Utah, USA

The corals of the Silurian included large, reef-building colonies that contained many thousands of individual animals. Some of the types of coral, though, consisted of just single coral animals, like the horn-shaped coral now within this layer. This kind of coral tells a very particular story of the Silurian world, if it is well preserved and is examined *very* carefully. The coral skeleton grows more quickly during the day, when the Sun shines and when the cohort of symbiotic algae in the coral tissues are photosynthesising, than at night. The outer part of the coral skeleton preserves this pattern as daily growth bands. The coral also grows more quickly in some seasons than others, and so these growth bands are clustered into patterns that, carefully interrogated, can betray the number of days in the year. For the Silurian, that was about 420 days, and so the Earth was spinning more rapidly then. The coral that now lies as ground-up powder in this layer, therefore, is also chronometer and astronomical recorder. (Its red colour, by the way, has nothing to do with its colour in life, but comes from iron minerals that percolated into it long after death, when it was deeply buried in strata; in geology, fossils can be buried, but they are by no means geologically dead.)

64 (430-420 Myr)
Early plant: *Hostinella* sp.
Poland

The trouble with soft land plants, like those which first evolved on our planet, is that they do not fossilise very easily at all. They decay quickly after death and recycle their carbon into the soil and into the air. To preserve some imprint of them, that can last underground within strata for many millions of years (and therefore that we can see, after such huge timespans), takes special circumstances: one can sweep plant fragments away in a flood and rapidly bury them within sediment, for instance. When this happens, the usual result is a blackened impression on a sandstone slab. This can tell you that it was a plant, but often not much else: most of the complex inner structure has typically decayed away. But combine such burial with some special chemistry of the sediment – for instance, *just* the right combination of iron and sulphur – and minerals can quickly form around microscopic features such as buried cell walls before they have chance to decay, and flash-petrify their microscopic structure. Just such a process happened, by chance (and much later, by even more improbable chance, was observed by a palaeontologist) with a specimen of *Hostinella*, a simple branched plant that appeared late in the Silurian Period. This showed that the special tube-like, water-conducting cells called tracheids had already evolved within the stem. Plants, thus, were seriously gearing up for their takeover of the land.

DEVONIAN
419-359 MYR

65 (415 Myr)
Bryozoa
Borshchiv, Podolia, Ukraine

There are groups of animals, both living and fossil, that have become part of our daily language: microbes, insects, fish, corals, mammals, dinosaurs – and perhaps even (in some company) trilobites and ammonites. Others, that may have been equally long-lived and important actors within Earth's biosphere, have stayed firmly in the shadows, at the edge of our usual consciousness (or well beyond it), to go centre stage only for a few academic specialists. We met one group in the Silurian – the supremely resilient, adaptable, and omnipresent ostracods. Let's introduce another one here: the bryozoans, which have been ocean dwellers on Earth (a very few have ventured into freshwater) for the best part of half a billion years and are still going strong. They're sometimes called 'moss animals', and form colonies of a dizzying array of geometrical patterns: fans, branching tubes, cabbage-like structures. The ones you will be most familiar with appear as whitish encrustations on seaweed on the beach, and these have a beautifully regular design if you look at them with a magnifying glass. What you see there is their calcium carbonate skeleton, and these creatures could be so abundant that their skeletons could pile up, to eventually build whole beds of limestone rock. The nice fossil example making up this layer lived in Devonian times, and went on to make part of a rock stratum in Podolia.

66 (415 Myr)
Tentaculitid, conical shell
Ukraine

We've now moved well on from those early of animal evolution in Cambrian times, when all kinds of short-lived experimental designs appeared. More than a hundred million years on in the Devonian, ocean life had settled into more familiar patterns – but that is not to say that there weren't a few mysteries still hanging around. The tentaculitids are one of them. They're not too uncommon as fossils in rock strata 500- to 400-million-year-old, and they're quite distinctive: high thin cones with a ribbed surface, usually less than an inch long, they were clearly the shells of some kind of planktonic animal of those times. But what? – for the soft body of the animal itself has never been found fossilised. Some kind of mollusc, perhaps akin to today's sea butterflies? Perhaps a worm? A distant relative of the brachiopods (for their shell structures, under the microscope, look a little similar)? Maybe some form of coral? All those ideas have been suggested, and tentaculitids remain an enigma.

67 (412 Myr)
Rhynie Chert rock
Aberdeenshire, Scotland

Who would have thought that a peat bog next door to a volcano could live to tell its tale? Live it did, and profusely – and then left a story that, some 412 million years later, became a key witness to how life finally conquered the land. The peat bog grew near what is now the village of Rhynie, in Scotland, and became permeated by the silica-rich waters from the volcano, which quickly converted it into the tough flint-like rock that is a chert – so quickly, in fact, that the peat-dwelling plants were preserved with their cellular structures intact, to look almost like modern biological specimens. Also petrified were a variety of small invertebrate animals that formed part of the terrestrial invasion force in those early days of the Devonian Period: exquisitely preserved mites have been found, and springtails, crustaceans, and harvestmen. One single specimen, known from just one fossilised head, was christened *Rhyniognathi hirsti*, and identified as the oldest known insect, and for good measure probably a *flying* insect, though no fossil wings were found. So was the air invaded so quickly after the land? Not so fast! – or indeed so high – came a riposte a few years later, after even closer study of this ghost-like head using the latest imaging techniques. This new study suggested that the *Rhyniognatha* head belonged not to a flying insect, but rather to an early, and emphatically earthbound, centipede. The Devonian skies, thus, might have been still empty of life.

68 (Devonian, precise age uncertain)
Favosites, honeycomb coral
New Mexico, USA

As the first properly coral-rich reef systems developed in Silurian and Devonian times, some of their fundamental patterns can be seen in the impressive rock and fossil record that they left behind for us to study. Reef systems are biological paradises, of course, and harboured then – as they still harbour now – a staggering diversity of organisms. On this biologically crowded stage, the main reef-builders must then make sure that they get their fair share (or, even better, an unfairly large share) of sunlight and nutrition to live and grow. They have, so to speak, to develop sharp elbows, to keep the competition at bay. One good way to do that is simply to grab all the available space on your patch, and colonial corals such as the *Favosites* entombed here in the urn were very, very good at this. It's a simple trick: divide to create the many individual animals ('zooids' in the jargon) of the colony, and keep these side by side with absolutely no space in between. This makes the honeycomb structure of this kind of coral skeleton: a style of construction subsequently adopted by many other corals, and other kinds of reef organisms too. It makes for a beautiful fossil to look at, an appreciation deepened by awareness of the territory-holding effectiveness of the animal that grew it.

69 (400 Myr)
Devon *Euruspirifer* and *Chonetes sacrinulatus*,
brachiopods
Germany

The brachiopods, those sturdy and successful clam-equivalents of Palaeozoic times, were going strong in the middle of that era, that is, within the Devonian Period. Take the *Chonetes* that lies scattered here, for instance. It has a nicely semi-circular profile, which is ten a penny in this fossil group. But look closely along the straight line where the two halves of its shell hinge together and – if the rock has broken kindly – you should see its diagnostic feature, a few thin spikes sticking out diagonally. With that, one can at least give it a name. But, this begs the wider question, of what use these particular spikes were to the brachiopod animal possessing them. The best guesses so far are that the spikes helped anchor the shell to the sea floor – and/or were some kind of sensory device, to give early warning of approaching danger. The fossil world is full of such tiny mysteries, which helps explain why, once someone has been bitten by the palaeontology bug, it generally stays a lifetime enthusiasm.

70 (390 Myr)
Paleozoic limestone, the major carbon repository
in the Earth's crust
Oriskany, New York, USA

Limestones are beautiful and complex rocks, often abounding in fossils, like the Onondaga Limestone of New York, from which corals, brachiopods, snails and nautiloid molluscs can be found. This limestone has a use as a building stone – on Brooklyn Bridge, for instance, and Syracuse University's Hall of Languages. Limestone in general, though, has a much wider and more profound use, for all of life on Earth. As a calcium carbonate rock, it is the largest buried carbon store in the Earth's crust, containing vastly more carbon than is present as carbon dioxide in the air. It is therefore the major factor preventing the Earth from having the truly hellish climate of our sister planet Venus (which has similar amounts of carbon to Earth, only that most of it resides in its dense, furnace-like atmosphere). This carbon store is not a static, permanent one: it is bound up in the Earth's rock cycle, within which carbon dioxide is taken down into the Earth as limestones form, and simultaneously released from its deep rocky stores back to the air by volcanism. For more than three billion years this delicate balance has allowed our planet to stay habitable.

71 (390 Myr)
Stromatoporoida, sponge
Ohio, USA

We revisit here another of the unheralded fossils – a stromatoporoid – that we left quite a while ago, in the Ordovician, where it was busy feeding and growing and, as its calcium carbonate skeletons piled up, building early reef systems. The best part of a hundred million years on, in the Devonian, its kin were still growing, and still helping to produce reefs. Indeed, if you visit a coral reef today, and search *very* hard in nooks and crannies and underwater caves, you might just happen upon something quite similar, a rarity called a sclerosponge. These are sponges that are not in the least spongy, being stiffened with calcium carbonate, and looking like knobbly orange marbles. Cut them open, and you can see layers, rather like tree-rings; similar layers (and knobbles too) can be found on the larger and more expansive ancient stromatoporoids. They are thus thought to be related to each other, though quite how closely is uncertain. If they are related, then the stromotoporoids might not have died out altogether, but retreated to a more reclusive lifestyle, in the twilight of their evolutionary lives. And – who knows? – perhaps their descendants might one day inhabit the reefs of the far future, too.

72 (390 Myr)
Ductina vietnamica, Phacopidae, trilobite
Hunan Province, China

Now, the trilobites, some 130 million years after they first evolved, were still around, but having a pretty thin time of it, all in all. The competition that had evolved in the meantime – the now omnipresent fish, ferocious sea scorpions and the like – made life hard for them. This particular trilobite, *Ductina*, had taken, along with quite a few of its kin, to keeping well out of the way in areas too unpleasant for most active creatures. Small, blind, it eked out an existence on dark, deep sea floors, where oxygen levels were generally low. It was a refuge of a kind – but not without its dangers. In a remarkable fossil occurrence, some related trilobites (also blind) from this kind of ocean zone were found petrified in long processions, nose to tail. Seemingly, they were trying to make their way to a safer part of the seabed as conditions worsened. Those fossilised examples didn't, alas, make it to safety. In perishing, they left us their eloquent story in the rock strata.

73 (385 Myr)
Osteolepis macrolepidotus
Sandwich Fish Beds, Orkney, Scotland

By the middle of the Devonian Period, fish were becoming common, and these were recognisably, even to our modern eye, fish-shaped fish: streamlined, with a covering of shiny scales and sets of fins and a tail more or less where you would expect fins and a tail to be. And these fish had now gone inland to live in rivers and lakes, following the plants and the invertebrates that were establishing the base of a large and complex terrestrial food chain. Life was moving on to land as a package. This particular fish, *Osteolepis*, is one of a fine assemblage of fossil fish that can be found in the flagstones of NE Scotland, that were originally layers of sediment on the bottom of a huge freshwater lake. The lake, like many of its kind, had oxygen-rich surface waters, and stagnant, oxygen-poor bottom waters. The fish that lived at the surface, on dying, fell onto the murky, scavenger-free lake floor. There, their remains became silted up and began to fossilise. The fins of *Osteolepis*, though, looked at closely, were not quite like those of most fish on a fishmonger's slab. They were made of a few large-ish bones, instead of many small ones. This was a fish with… possibilities. It, or one of its close relations, would eventually use that sturdy fin to see what life out of water might be like.

74 (380 Myr)
Stromatoporoids, coral, bivalves
Belgium

Belgium has marvellous outcrops of Devonian rocks in the southern part of the country, which represent this period of time rather better than do those of Devon, from which the name was originally coined (indeed, many of the subdivisions of Devonian time used by geologists, such as the Famennian and Givetian Ages, are named after places in Belgium). Therefore, UNESCO has been active in this rocky terrain too, and set up the Famenne-Ardenne Global Geopark to celebrate these riches of Earth history. Perhaps the most spectacular part of this geopark are the limestone mountains at its heart, the fossilised remains of the huge stromatoporoid and coral reefs that flourished there in mid-Devonian times. This ancient geography, long-buried and now exhumed in the modern landscape, has developed new resonances. Subterranean water, coursing within it, has carved some of the largest cave systems in Europe.

75 (380 Myr)
Rugose, 'solitary coral'
Morocco

While most of Britain, in Devonian times, was land with deserts, lakes and rivers – part of a larger landmass sometimes called the 'Old Red Sandstone continent' – elsewhere, there were warm seas. Indeed the sea lapped up onto the edge of this landmass in what is now Devon, and it is from the strata that remain that the Devonian took its name. Go to the seaside at, say, Ilfracombe, and you might find some fossil corals from those times along that rocky shoreline. The long-vanished Devonian seas are more widely represented as rock strata elsewhere in the world, though, and they include representations of some remarkable kinds of sea floor. In the Anti-Atlas Mountains of Morocco, for instance, large masses of fossil coral (like the coral now lying within this layer) may be found. The patterns in which these corals are found suggest that they were clustered around 'hot vents' – fractures in the sea floor through which hot volcanic water was bubbling up. This is an environment rich in nutrients – but also a dangerous one of heat and toxic chemicals. One way for the corals to survive was for new baby corals to take shelter within the dead skeletons of former coral generations. Life will generally find a way, even in the toughest conditions.

76 (380 Myr)
Stringocephalus, brachiopod
Guangxi, China

Fossils provide marvellous testament to the life millions of years ago, allowing one a glimpse of what long-vanished sea floors really looked like. But they serve a more practical purpose, too, as precise chronometers, to allow the almost endless archive of the Earth's rock strata to be placed in proper order – which in turn allows the history of the Earth to be properly told. The handsome brachiopod (or 'lamp-shell') that now lies here, *Stringocephalus*, is a fine example of such a timekeeper. It is characteristic, not just of the Devonian Period (a 60-million-year-long slab of time) but of just one part of it, the Givetian Age, which spans only 6 million years in the middle part of the Period. This particular specimen comes from China, but find *Stringocephalus* elsewhere in the world – in Belgium, say, or Germany, or Russia, or North America, or North Africa, or Australia (it has been found in all these places, and more) – and you can confidently say that the rock strata in which you found it will belong to that same modest time-slice. In searching for this particular fossil, though, one needs to bear in mind where it would live, and where it wouldn't. *Stringocephalus* liked shallow seas – and in particular the calm areas just on the leeward side of a coral reef, where it thrived. So, in rock strata suspected to be Givetian that represent deep seas, or river plains, or lake floors, other fossil timekeepers will need to be sought to prove the age. It's a grand puzzle, and all part of geology's housekeeping.

77 (380 Myr)
Cyanophyta, horse-tooth stromatolite
Orkney, Scotland

Even as complex, multicellular life was in full swing, both in the oceans and – more lately – on land, echoes from the deep past kept returning. For the first three billion years of life on Earth, the fossil record is dominated by those distinctively layered rocky microbial constructions, the stromatolites (the NASA exobiologists will be scouring the rover images from Mars for similar things even now, hoping to see signs of ancient life on that planet). When the worms, and snails and other such creepie-crawlies appeared on Earth, a little more than half a billion years ago, the stromatolites mostly moved out – mainly because they were being eaten. But, they would come back to set up shop again when conditions allowed. In the enormous 'Orcadian' lake that covered much of what is now north-east Scotland in mid-Devonian times, microbial colonies coped well with conditions on the shoreline of that lake, while more complex life struggled with the frequent swings there between wet and dry, warm and cold. And so the stromatolites began to grow there, ultimately to form small microbial reef systems at the edge of that lake. These fossil structures may not be as striking to us as, say, the beautifully preserved fossil fish with which those lake strata abound. But they are eloquent in their way, in what they tell us about how truly ancient and more modern organisms can co-exist, at places where life's various boundary conditions meet.

78 (375 Myr)
Bothriolepis canadensis, placoderm, armoured fish
Pennsylvania, USA

By Devonian times, those ultimate slow starters of the animal kingdom, the fish, were becoming common in both saltwater and freshwater, many as fast swimmers of more or less familiar (to us) fishlike form. Even into late Devonian times, though, some monstrous-looking heavily bone-clad fish of archaic pattern persisted, as part of this new fishy menagerie. The *Bothriolepis* here is a lovely, grotesque example. With an armour-plated box-like body and two long armoured arm-like fins, it is of the kind that had the nineteenth-century savants that first unearthed them waxing lyrical on their fantastical form. They first wondered whether they were some kind of ancient tortoise, or giant beetle, before pinning them down as fish. Bizarre as it was, *Bothriolepis* in its time was a successful denizen of lakes and rivers (and some ventured into the sea too) and, for all of its ferocious appearance, likely just grubbed in mud for plant debris to make a living.

79 (370 Myr)
Lithostrotionidae, colonial coral
Poland

Lithostrotion is something of an oddity as a coral – a family misfit, one might say. It belongs to the rugose corals, one of the two great groups of corals that spanned much of the 200-plus million years of the Palaeozoic Era. Most of the rugose corals were solitary – thus, one animal per 'colony' with horn- or cylinder-shaped skeletons that could approach a metre long. But *Lithostrotion* bucked this trend to become a proper colony, each composed of many individual animals – and thus took on the lifestyle of the other great Palaeozoic coral group, the tabulate corals, which were almost all colonial. *Lithostrotion* did well, too – especially in the succeeding Carboniferous Period, for it now forms one of the classic fossils found in strata of that age.

80 (365 Myr)
Rhacophyton condrusorum
Belgium

As a plant, you finally managed the trick of survival away from the sheltering, stable warm bath of the oceans, to live on the hostile, fickle environment of the land surface. A few layers back we encountered that terrestrial pioneer *Cooksonia* of Silurian times, little more than straggly, branching green stems rooted into the land surface. What next? Well, one form of self-improvement is to be able to capture a little more of that life-giving sunlight, by stretching parts of those branches into wide flat surfaces to make the equivalent of solar panels: to begin to evolve leaves, in other words. And this is what *Rhacophyton* was doing, in the late Devonian Period, as it grew frond-like extensions to become something like a fern. Was it a fern, really? Opinion is divided. Its frond-ish structure is crude by comparison with the kind of sophisticated fronds one sees on modern ferns, so perhaps it's best thought of as an almost-fern. This prototype was successful, though, and built masses of shrubby vegetation, a metre or more tall, over parts of the Devonian landscape that suited it, such as river floodplains. This prolific growth brought with it a quite new kind of danger. *Rhacophyton* has been associated with some of the first wildfires detected in the geological record – a victim, when the dry season came, of its own success.

81 (365 Myr)
Orthoceras, 'ink fish'
Atlas Mountains, North Africa

Some of the latest layers in this artwork have been stories of persistence: of the trilobites in the lengthy twilight years finding a haven in deep dark seas, and the sponge-like stromatoporoids still help finding space among the burgeoning corals to help build lush reef systems. There is another one here, of an orthoceratid, one of those be-tentacled molluscs in its long, straight, seemingly terribly ungainly shell, still thriving in Devonian times – even when the new kids on the block had appeared and were firmly in place. The specimen that now lies here comes from Morocco's Atlas Mountains. From the magnificent fossil beds on which occur rock slabs with many examples of this archaic form, right next to specimens of its more evolved kin, the nautiloids, in which the shell had not just curved, but coiled into a beautiful spiral. Neater, more finely tuned hydrodynamically, these nautiloids would go on to be truly durable (to persist until today) and prolific (to give rise to the iconic ammonites of dinosaur times). But, one can't resist a cheer for their straighter, clumsier, more antique kin, as they have their (almost) last hurrah in the warm Devonian seas.

82 (359 Myr)
Mudstone containing fossilised fernlike plant spores, Late Devonian Extinction
Eastern Greenland

The Devonian Period was a time when life bloomed in the oceans – one thinks of those coral-rich reefs – and also spread over land, as plants and animals finally began their long-delayed conquest of that hostile terrain. But this blossoming was to come to a halt, as Earth's living environment was shaken by a set of violent perturbations that played out over more than ten million years, and that amounted to the second of the 'Big Five' mass extinctions of the past half-billion years. What happened? There is no clear evidence here of gigantic volcanic outbursts or cataclysmic meteorite impacts. Rather, there are signs of global climate changes, as glaciations alternated with intense global warming events. This layer is made of rock representing the latest of these extinction pulses, at the end of the Devonian Period. It contains curious evidence, which points to a most singular kill mechanism. The rock is a shale, once a layer of mud on a lake floor that formed during a phase of global warming. It contains fossilised spores, many of which are malformed, in a way strongly recalling high levels of UV radiation damage. That, in turn implies a temporary loss of Earth's protective ozone layer, as one of the effects of that sharp global warming spike. Among the fallout was the decimation of the coral reefs and of the Earth's infant forests. From this devastation there slowly emerged the world of the Carboniferous Period – our next stopping point in this narrative.

CARBONIFEROUS
359-299 MYR

83 (330 Myr)
Sea floor: bivalves, shells, sponges
Elie, Scotland

Around 330 million years ago, quite a bit of what is now known as Britain was covered by warm shallow seas and shorelines, of the kind that these days form attractive holiday destinations. There was a nice range of sea floor life too, a selection of which now lies in this urn layer. It was a classical subtropical scene: not because the whole world was warmer at that time, but because Britain then was subtropical, and indeed lying south of the Equator. That location, several thousands of kilometres away from where Britain is now on the globe, is revealed by the position of microscopic iron minerals in the rocks. These act as tiny, fossilised compass needles, and – when interrogated by the right kind of shiny analytical machine – preserve the pattern of that ancient magnetic field in Carboniferous times, and so provide a clue to Britain's former geographic position. Britain, over time, was then slowly drifting north, being carried on its tectonic plate. It won't be long before we catch up with it again, in the urn, when the Equator is crossed.

84 (327 Myr)
Pentremites sulcatus, giant blastoid
Tennessee, USA

Those warm, shallow, Carboniferous seas held some more or less familiar kinds of life, like the sponges and corals, though their particular kinds were different from those of today. They also had some animals in abundance which are now rare, like those 'lamp-shells' the brachiopods, and the elegant 'sea-lilies' or crinoids. The crinoids are not lilies or any other kind of plant, but relatives of starfish and sea urchins. They have now mainly retreated to deep cold waters, such as off Antarctica, but in the Carboniferous they could be so common that they built up thick rock layers, mostly made of the broken remains of their long stalks, looking like a mass of pipe-stems. The Carboniferous was also a good time for their less well-known relatives, the blastoids, one of which now lies here. Now extinct, these looked in life a little like many-armed sea-urchins at the end of short stalks, and seem to have lived in a similar way to the crinoids, by filtering small plankton from the seawater. Blastoids are generally regarded as one of the minor kinds of fossil, but they did evolve a unique structure to extract oxygen from seawater, the equivalent of gills in fish or (in air) our own lungs. Called the hydrospire, it is hidden inside the skeleton and ferociously complex in pattern – a geometrical puzzle for palaeontologists.

85 (321 Myr)
Annularia filiformis, pteridophyte, the leaf whorls of an extinct horsetail
Eastern Europe

By Carboniferous times, mighty forests had developed on Earth and – by a quirk of biology and geology – became key to the Industrial Revolution of the human species, more than 300 million years later. Many of these forests grew in huge equatorial swamps that stretched across from what is now North America, to Europe, to Russia, to China. Buried and compressed, countless generations of these forests became transformed into thick and profitable coal seams worldwide. *Annularia* is a characteristic part of the Coal Measures vegetation – or rather part of a part, for the name refers to the characteristic rings of radiating leaves, attached to a stem that was given the separate name *Calamites*, before it was realised that they were part of the same plant. Together, they make up a horsetail, rather like the ones in our gardens – only monstrously sized, reaching ten metres tall. These were alien forests to our eyes: lush, and with such disorientating large horsetails, together with gigantic tree-ferns and club-mosses – but no flowers, no birds. To reach another planet, one only has to look beneath one's feet.

86 (318 Myr)
Lungfish
Crock Hey Coal Mine, England

Sometimes it's good to be a stick-in-the-mud, even as the newer models race past you. The lungfish, which do have serviceable lungs, are part of a group of fish from which, late in Devonian times, there appeared the 'fishopod' *Tiktaalik*, that pioneer in exploring dry land. From *Tiktaalik* and its kin were to come all other land-dwelling vertebrates, including the dinosaurs, the mammoths – and us too. But the lungfish themselves just kept going, for over four hundred million years. Their lungs stayed functional, though wouldn't manage Olympic sprints, while their bony fins didn't develop into arms or legs, but just stayed as flipper-like fins, to splash about in shallow water, to crawl onto a mudbank, or to burrow deeply into mud to survive the dry season. This specimen lived in a Carboniferous swamp that, much later, became a coal seam in Lancashire. You can still find lungfish splashing and crawling in swamps in Africa, South America, Australia. Meanwhile, the dinosaurs have come and gone, and the mammoths have come and gone (while for us humans, it is too early to say).

87 (318 Myr)
Stigmaria, tree fern root
Crock Hay Open Cast Mine, Wigan Lancashire, UK

Forests do more than just grow, and provide shelter for their animal inhabitants, whether today or in the Carboniferous. They have other roles at the Earth's surface. One of these roles comes to mind when thinking of the fossil in this layer: the fossilised root system called *Stigmaria*, often found among the coal seams of Carboniferous strata. These are large fossil roots, often thicker than a human's arm, with little spiral pits on them (where the rootlets came off in life). It was later realised that these roots belonged to stems of enormous, tree-sized club mosses – but their significance goes beyond another bizarre (to our eyes) element of the coal forests of the Carboniferous. *Stigmaria*, and other root systems, held the trees in place, true – but they also held the soil in place. This interlacing network of tough root systems protected the land surface, far more than was the case with the barren, easily erodible landscapes before the invasion of plants and animals. One consequence was that rivers found it much harder to carve new channels through this new, more resistant kind of land surface, and so were forced to change their behaviour. Before the forests arrived, most rivers had many channels in a shifting, braided pattern. Once the forests, and their roots, developed, the rivers tended to have just one channel that meandered slowly across its floodplain. It shows the power of trees.

88 (318 Myr)
Stylocalamites cistii, tree-like horsetail
Poland

As a palaeontologist, when you are faced with all of the different types of fossil plant in the Carboniferous coal strata, how do you begin to put them into order? It's a slow and patient business with fossils, to learn to classify them and to recognise the different types, especially so because mostly all that can be found is fragments. In those ancient forests, there were many different kinds of horsetail, some true giants up to 20 metres high, others smaller and bush-like. They're all generally put into the genus *Calamites*, and had a vertically-ridged stem that pulled apart into segments, like the horsetail in your garden (a true living fossil, if in miniature) with thin leaves radiating out where the segments join, while the larger ones often had side branches coming out of the joins too. There are four subgenera of *Calamites*, and you can recognise the one here, *Stylocalamites*, because it has no marks of side branches coming off at the joins. *Stylocalamites* includes a few distinct species, and this one, *Stylocalamites* cistii, has distinctively long stem segments. It's all a matter of identification.

89 (317 Myr)
Sigillaria lorwayana, coal bark
Wooley Pit, Yorkshire, England

Today, the lycopods, otherwise known as club mosses, are small green plants, but in the Carboniferous tropical swamps, they were tree-size giants. The characteristic vertical striping of the bark on the stem of one such lycopod tree, *Sigillaria*, is one of the more recognisable fossils among the coal strata of that age. These were true tropical forests, with supercharged vegetation growth that, once, buried, compressed, and heated deep underground, were to become the thick coal seams that we still exploit today. Britain, carried along on its tectonic plate, had, by then, drifted north to lie pretty well on the equator, and thus entered the hot humid climate zone associated with this latitude. These conditions were not to last, for the northward drift was to continue.

90 (316 Myr)
Trigonotarbid, arachnid, armoured spider
GZW, Upper Silesia Coal Basin, Orzeskie beds, Poland

While amphibians were splashing about in the coal swamps of the Carboniferous, the invertebrates of the land were evolving too – at times to just as impressive a scale. One would be wary of the two-metre-long millipede, *Arthropleura*, that lived in those times, though might be relieved to learn that it was (probably) a herbivore. And those dragonflies with half-metre wingspans really did exist (they were not *precisely* like today's dragonflies, but quite close enough for our purposes). The urn specimen here may not be quite as spectacular as these, but may be a little more representative of typical coal swamp invertebrates. It's a trigonotarbid, which looked in life rather like a large muscular spider – think of a cross between a Teletubbie and a tarantula – and indeed was an arachnid, and so quite closely related to spiders, and to scorpions too. Like spiders, the trigonotarbids seem to have been mostly predators, though lacking spinnerets, they didn't spin webs. Why did all these creepy-crawlies grow quite so big? One idea is that the air contained a little more oxygen in those Carboniferous times than today, which would have helped them breathe. That richness in oxygen might not have been *altogether* a good thing, as we will see.

91 (315 Myr)
Carboniferous bituminous coal
Lancashire, UK

The world-spanning coal seams of the Carboniferous have been dug out of the ground and burnt in huge amounts, to drive our economies, since the Industrial Revolution. We realise now that this conversion of carbon in the ground into carbon dioxide in the air is causing global heating ('warming' seems too gentle a word) with all the dangers that this brings. Back in the Carboniferous, the opposite was taking place. The spreading forests of those times were pulling carbon dioxide out of the air and, as generation after generation of these forests were buried to begin the process of forming coal, they were taking that carbon down into the ground with them. As a result, levels of carbon dioxide in the atmosphere fell, and the Earth cooled – and entered a glaciation that was to last for some fifty million years. The ice did not cool the tropical areas where the coal was forming, just as the tropical forests of Africa and South America are still hot, wet, and luxuriant even if there is thick ice on Antarctica and Greenland. But, the spread of Carboniferous polar ice was still to have an effect on the coal swamps, even at long range.

92 (315 Myr)
Lycopod bark, clubmoss imprint
Poland

This piece of lycopod tree is just a minuscule part of the petrified forest system of the Carboniferous, being in effect a tiny sliver of coal carrying a bark-impression. The coal is mostly made of carbon that, as carbon dioxide, was taken from the air by that tree to grow its woody tissues. The tree, in photosynthesising, gave oxygen back into the air. But then, instead of decaying and thus combining with that oxygen once more to release carbon dioxide back into the air, it, and billions of fellow trees, buried that carbon as coal strata. So, that extra oxygen stayed in the air, and its levels built up, likely to levels higher than today. One result of this oxygen-rich atmosphere in Carboniferous times was the possibility that millipedes and dragonflies could breathe more easily, and so could grow larger. Another is that those forests, sparked by lightning, burned easily and often. You can see the result of this when you pick up a piece of coal: the part of it that leaves a sooty mark on your hand is fossil charcoal from those ancient fires. It is, one might say, an incendiary connection between ancient and modern times.

93 (312 Myr)
Ammonoid and gastropod fragments
Boggy Formation, Oklahoma, USA

The coal seams of the Carboniferous are arranged in a curious pattern. Above each coal seam, there is a layer of dark mud with fossils of marine animals, such as the mollusc remains in this urn layer, showing that the coal forest must have been drowned by the incoming sea. Then, above this, layers of delta sand show that the land was building out again on top of these marine muds, on which eventually another forest grew – only to be suddenly overwhelmed by the sea in turn. It was a repeating pattern of alternation of land and sea, that the puzzled geologists studying it called 'cyclothems'. But what caused them? The answer became clear when evidence – fossil boulder clays, ice-scratched rock pavements and such – of a huge Carboniferous icesheet was found in South Africa and South America (which were then conjoined and lying over the South Pole). As this southern icesheet waxed and waned, it drew water out of the oceans, and then released it again, many times over. And so, many times, global sea level rose – to drown the distant forests of the tropical zone – and then fell – to leave their buried remains high and dry, for another forest to grow. It was a whole planet, acting like clockwork to build its own geology.

94 (311 Myr)
Euproops, horseshoe crab
Illinois, USA

When one looks to the closest living relatives of the trilobites, those most iconic fossils of the Palaeozoic Era, the horseshoe crabs that live in some shallow seas today are usually put on top of the list. Despite the name, they are not crabs, or any other kind of crustacean, but a different group of animals. Horseshoe crabs do look somewhat trilobite-like, being roughly tri-lobed and with a magnificent head carapace that does indeed have a horseshoe-like outline. One can also sometimes find them as fossils in ancient strata. This specimen from the Carboniferous Period, *Euproops*, looks very similar to those that live today. And as living fossils that we can observe in their natural habitat, they help shed light on their ancient cousins the trilobites too, sometimes in the quirkiest of ways. Modern horseshoe crabs, for instance, often crush their prey between their legs – a rather bizarre form of attack, perhaps, but one that some scientists think might therefore have been used by trilobites too. It's just another of the oddities that one can stumble across, in building up a picture of the past.

95 (311 Myr)
Essexella, Scyphomedusae, Medusae, jellyfish
Kentucky, USA

Among the coal beds of Illinois, that have been widely strip-mined, there is a rock layer at a place called Mazon Creek with large iron carbonate concretions. Split these open and (with luck) you can find fossils with not just shells and bones, but petrified soft tissues too like skin, guts, and eyes. The most celebrated fossil here is *Tullimonstrum*, the 'Tully Monster', which looks like a Hollywood director's fevered image of the Loch Ness Monster, though the dramatic effect may be a little weakened as it is not much more than six inches long. It's a real mystery – is it a weird fish, or a mollusc, or strange worm? All these possibilities have been suggested. This fossil from those celebrated strata is maybe less enigmatic, but shows similar exquisite preservation. It is the jellyfish *Essexella*, an animal that, like modern jellyfish, was entirely soft-bodied and so in normal circumstances is only very rarely found as a fossil. *Essexella* from the Mazon Creek strata is one of the few fossils to have been celebrated in verse ('Ode to a Blob'). With some specimens showing the petrified remains of tentacles, it is, though – one hastens to add – a most remarkable blob.

96 (310 Myr)
Spiropteris species, immature fossil fern
North West Europe

In the Carboniferous, leaves – those ancient forms of solar panel – were developing some of the shapes which are familiar to us today, not least among the many kinds of fern that were evolving then. This particular specimen has been given the name *Spiropteris*, or 'spiral leaf' for it is in effect a fern crozier, or fiddlehead: that is, the young coiled leaf of a fern before it spreads out as a frond. Like many named fossil plants of the Carboniferous, it is part of a larger plant, the tree fern *Psanorius* (which also has a distinctive kind of root, to which the name *Tubiculites* has been given). Today, fern croziers are delicacies in some kinds of cuisine as 'fiddlehead greens', with all kinds of health-giving properties such as omega-3 and antioxidants. Whether the *Spiropteris* of Carboniferous times was as nutritious is quite unknown.

97 (310 Myr)
Cordaicarpus species, *Cordaites* seed with *Calamites* branch
Eastern Europe

Several innovations took place among plants in the Carboniferous, as the land became progressively clothed in vegetation. The plant fossil *Cordaites* represents two of them. Geologists usually associate the name with long, strap-like fossil leaves, which can be common in coal-bearing strata. The leaves, though, are only part of a tree that could reach 30 metres high, and that may have been the first conifer. And, unlike many other Carboniferous plants, which produced spores, the *Cordaites* tree reproduced by means of seeds; these seeds, in true palaeontological fashion, were given the separate name of *Cordaicarpus*, a specimen of which now lies in this layer. Seeds have several advantages over spores. A spore is just a single cell, but a seed is already a complex, multicellular embryo, protected by a seed coat and often carrying food resources with it, to give it a better chance of survival. The *Cordaicarpus* seed was winged, and heart-shaped. That seems a most appropriate shape to be, to symbolise the promise of this evolutionary step.

98 (310 Myr)
Pteridospermatophyta, seed pods, extinct seed-bearing plant
Harmanville Mine, Pennsylvania, USA

Seeds were such a good invention, that they developed in more than one group of plants during the Carboniferous Period. One such group was the pteridosperms, more commonly known as 'seed ferns'. The name is a little misleading. These were not true ferns (which only produce spores, not seeds), and probably they were not even very closely related to ferns. But fossil leaves were found among the coal strata that looked very much like fern fronds, and that did have fossil seeds attached to them, and so the name 'seed ferns' stuck. However they fitted into the overall evolution of plants (there is still debate about that), the seed ferns were a successful group, and lived for quite a time after the Carboniferous, though they are now extinct. As biological innovators (even as quite mysterious ones) they certainly deserve their place in this artwork.

99 (309 Myr)
Batrachichnus plainvillensis, amphibian footprint
Massachusetts, USA

How much can you tell from a fossil footprint? This kind of study is a riddle wrapped around with many puzzles. What animal made it, for instance? This question is difficult, as the conditions in which footprints are preserved into strata (a drying mudbank surface, just the right consistency to be pressed into a print shape from a passing animal, and then quickly buried by another sediment layer before the print disappears) are usually not the same as those in which the bones of the animal itself might be fossilised. So we are left to ponder the print itself: in the case of this urn specimen, *Batrachichnus plainvillensis*, lines of paired small, spookily hand-like prints with five short fingers. Who or what might have been the culprit? The late Carboniferous was a time when quite a few kinds of amphibian were exploring the land, though never straying too far from water. Perhaps one of the several modest-sized kinds living then, about 20 centimetres long? *But*, it has been suggested too, this particular kind of *Batrachichnus* might have been made by baby amphibians that would grow into impressively larger adults, like the ferocious carnivore *Eryops*, to reach two metres and weigh 90 kilos. It's a nice puzzle to have – but in either case, the general picture is clear: the animal invasion of land was afoot.

100 (309 Myr)
Bellerophon, gastropod
Kansas, USA

The formal names given to fossils, and to living plants and animals too, can sometimes give telling insights into how science (and scientists) work and think. Take *Bellerophon*, for instance, the name given to the particular kind of fossil snail preserved here. It is quite handsome, as snail shells go, but it seems a stretch to name it after Bellerophon, that most intrepid hero of ancient Greek mythology who, among other feats, killed the monstrous Chimaera and tamed the winged horse Pegasus. But the man who gave that formidable name to this modest snail had an eye for the fantastical. This was the French naturalist Pierre Denys de Montfort, working at the beginning of the 19th century. His work on molluscs ranged from humble snails and clams, to pursuing evidence for the kraken, the ship-devouring sea monster of legend. His claims were scoffed at – only to be vindicated decades after he died in poverty, when the existence of the giant squid was finally confirmed. So we can cherish the fossil *Bellerophon*, as monument to a bold and adventurous mind.

PERMIAN
299-252 MYR

101 (300 Myr)
Red Permian sandstone
Ballochmyle Quarries, Ayrshire

Late in the Carboniferous Period, the great coal forests were dying. There are a few reasons for this, but one was simply the inexorable northwards drift of the tectonic plate which Britain was part of, out of the Earth's humid equatorial zone and into the arid desert belt of the northern subtropics. In a striking change of the landscape, those lush swamps dried up, and were replaced by windblown desert sands (of which a handful are in this urn layer) with here and there a salt lake, shrinking in the baking Sun. As the forests disappeared so did the luxuriant life they harboured. Indeed, there are so few fossils in these desert sandstones of Ayrshire – that now, naturally cemented after nearly a third of a billion years underground, make such a good building stone – that those geologists are not quite certain if they formed late in the Carboniferous Period, or early in the Permian. Such chronological uncertainty is a common problem in strata that formed in desert regions, and adds to the sense of mystery surrounding them.

102 (292 Myr)
Eryops, amphibian
Oklahoma, USA

We met baby *Eryops* a few layers before, and late in Carboniferous times – or perhaps not, for that depends upon the identity of the animal that made those enigmatic *Baratrachichnus* footprints. So, whether this is a first or second meeting, we might take a closer look at this impressive animal. It may not have been the most advanced animal for its times, being an amphibian and thus dependent on water, at least in its tender larval stage (other animals had by then developed the trick of producing eggs with tough shells, to be able to venture farther into dry land). But within its limitations it was muscular, heavily boned and active, and one of the most formidable predators of its day; it probably occupied much the same sort of ecological niche as crocodiles and alligators do today. Its teeth were wickedly strong and sharp, and had a curious structure that now make *Eryops* and its kin instantly identifiable: the enamel is intricately infolded with the dentine, to give broken surfaces a minutely labyrinth-like appearance. Palaeontologists, glad of such a distinctive character, often call these animals 'labyrinthodonts'. The labyrinthodonts – a large and diverse group of which *Eryops* was just one member – were to be successful for quite a while, in those times before the dinosaurs walked the Earth.

103 (292 Myr)
Metalegoceras, Metalegoceratidae, Ammonoidea, mollusc
East Timor, South East Asia

When one studies Permian strata in Britain, that 'New Red Sandstone' which formed in pitilessly arid deserts, it can be easy to forget that elsewhere in the world, at that time, there were seas and forests abounding in life. What is now East Timor, for instance, was a warm shallow sea. Among the many creatures living in it were some fine ammonoids. These had not yet evolved to become the ammonites that were to be so symbolic of the Mesozoic Era to come, but at a quick glance they looked quite similar: elegantly spirally coiled shells with, in life, a protruding betentacled head, to show that these were relations of squids and octopi. The ammonoids did well in the Permian seas, as mid-ranking predators. Their many kinds evolved quickly too, so now their fossils have become one of the best chronometers to date the strata of the Permian. This kind of dating work does not need any kind of sophisticated analytical machine – just a palaeontologist with the skill to find these fossils in rock exposures, and the experience to know which of the hundreds of specialist articles and thick monographs to thumb through, to precisely identify the correct species (with luck and a lifetime's experience, that very species might be instantly recalled from memory, even from a fragment). It's absorbing work, but not for the impatient.

104 (290 Myr)
Agathoxylon
Pfalz, Germany

Fossil wood, if it's not attached to such things as fossil leaves, can be hard to identify precisely, but the petrified trees called *Agathoxylon* were impressive things, the trees in life reaching 50 metres or taller. They were conifers, and more precisely members of the araucarian family. The araucarians would go on to be very successful later, in the times of the dinosaurs, though these days there are only a few kinds left (the monkey-puzzle tree is one), mainly native to the Southern Hemisphere. Here, we are near the start of this mighty forest empire-to-be.

105 (286 Myr)
Mycterosaurus longiceps, synapsid vertebrate
Oklahoma, USA

By the Permian, the dinosaurs hadn't yet arrived, but one could be forgiven for thinking that they had, for a characteristic animal of the time was *Dimetrodon*, that unmistakable sail-backed beast which features in every child's collection of toy saurians. But *Dimetrodon* – and its relative *Mycterosaurus*, a bone of which lies in this urn layer – wasn't a dinosaur. It was a synapsid, a group of animals which used to be called 'mammal-like reptiles' and which were the dominant land animal group in the Permian. They weren't reptiles, though, but they did have some mammal-like characters, like teeth that were beginning to develop into different types such as incisors and canines. Indeed, according to modern classification, we and all other mammals can be included in the synapsids too. So one might think of *Mycterosaurus* – and *Dimetrodon*, too – as proto-mammals, which puts a somewhat different light on that child's collection of toy dinosaurs. The less famous *Mycterosaurus* was not as impressive as its sail-backed cousin, being about the size of a house cat, if rather more ungainly. Nonetheless, one can celebrate it here as a pioneer within a line of animals that would – quite some time later – make waves upon the world.

106 (285 Myr)
Gyrospirifer condor, brachiopod
Bolivia, South America

The world of the living and the world of the long-dead can sometimes combine in the most curious of ways. This layer features Alcide d'Orbigny, that most indefatigable of globe-trotting 19th century palaeontological savants. Charles Darwin once grumbled, on hearing that d'Orbigny had reached South America before him, that he would find all the best specimens. Well, Darwin did find a few that had been left in D'Orbigny's wake. But, to make the point, here was D'Orbigny in Yarichambi, on the Bolivian plateau four kilometres above sea level in 1842, noticing the native people using what they called eagle-stones, collected from the Andean rocks. An eagle-stone was placed upon the wrist of a pregnant woman, so the baby would survive to be born. D'Orbigny recognised the eagle-stone as a fossil brachiopod, that he called *Spirifer condor*, as the native people saw in it the shape of that giant bird, that soared above them. He knew that it was an ancient fossil, but it was unlikely that he recognised it as Permian, for that geological period had only just come into existence: it had been founded the previous year, by another of those remarkable early geologists, Sir Roderick Murchison, while travelling on the other side of the world, in the Perm region of Russia. *Spirifer condor* later became *Neospirifer* and then *Gyrospirifer*, as later palaeontologists disputed details of taxonomy, but the condor remains, tribute to the eagle-stone.

107 (285 Myr)
River floodplain sandstone from the supercontinent Pangaea
Robledo Mountains, New Mexico

It's a piece of sandstone – or at least it was, until it was ground to powder to be re-sedimented as this layer. Now, let's put it back into its natural surroundings, which was a sand-bar in a river in what is now New Mexico, about 285 million years ago. Then let's pan out, and see that river set within mountains, which have long ago been eroded away (bits of them will go on to form grains in more river sandstone). Let's pan out again, wider and wider, and the landscape will go on and on and on, with more rivers, mountains and deserts – eventually stretching out across half the world. This sandstone was a minuscule part of Pangaea: the mightiest supercontinent of the past half-billion years, which in Permian times brought together all of today's major continents: North and South America, Eurasia, Africa, India, Australia. Pangaea had gradually formed over the past hundred million years as oceans closed, the ocean floor crust sliding down into the depths of the Earth's mantle, to the accompaniment by earthquakes and volcanic eruptions, bringing these different continental blocks together. Now it was complete: so large that clouds could not reach its distant interior, which became a vast desert. (The assembly of Pangaea, and the spread of drought, is another reason for the disappearance of the coal forests that had spread so widely and lushly in the preceding Carboniferous times.) The world had changed, and on the grandest scale.

108 (277 Myr)
Permaster, starfish
Victoria, Australia

The starfish *Permaster*, as re-fossilised in this urn layer, is a nice example of the kind of animal that lived in late Permian seas, and – as so often in the realm of palaeontology – shows a quirky detail of starfish biology as a bonus, for those with patience enough to take a very close look. Small enough to fit in the palm of your hand, its classic 5-armed skeleton is nevertheless sturdily constructed – and came with its own repair kit. On the very first *Permaster* specimen to be described and named, the limy plates at the very end of the longest preserved arm are smaller than the others. This particular animal was clearly fossilised in the act of regenerating an arm lost in combat on that Permian sea floor, showing that the starfish trick of being able to re-grow lost arms goes back to very ancient times.

109 (260 Myr)
Glossopteris, seed fern
New South Wales, Australia

Among the fabled trees of legend are Yggdrasil, the old Norse tree of life, and the whispering oak Dodona, a branch of which – through the goddess Athene's intervention – helped carry Jason's Argonauts across the waters. *Glossopteris* would sit well in such company, being now legendary in Earth's narrative. It was decidedly not mythical, though, having a solid reality in time and space that, in human minds, helped rebuild a supercontinent. *Glossopteris* was a seed-bearing fern tree, with distinctive tongue-like leaves. Its fossilised remains were noticed by the sharp eye of Eduard Suess – one of the grand figures of 19th century geology who took the whole world as his working domain – in Permian strata from North America, to Africa, India, Australia. These continents are now scattered across the globe and, through long isolation, each has developed its own distinct flora and fauna. So why, Suess asked, did they all share this same kind of plant in the Permian? They must, he said, have been joined together then, in a mighty landmass that he named Pangaea. This was a leap in the dark, made well before talk of continental drift or plate tectonics. But Suess's vision has stood the test of time, and has strengthened as more evidence was unearthed. One such piece in the Pangaea puzzle was added when *Glossopteris* was found in Antarctica by the Scott's doomed expedition. The explorers did not live to tell this tale – but their fossil specimens, later found in Scott's tent, remained as mute witness to their discovery.

110 (262 Myr)
Stegocoelia, gastropod and bivalve
Oklahoma, USA

The Permian world was soon to end ('soon' being in about 10 million years, this being geological time that we're talking about), as indeed was the entire, quarter-billion-year-long Palaeozoic Era, of which the Permian is just the last one-sixth part. But, for now, life was continuing more or less peacefully, and many of the humdrum foot soldiers of the Palaeozoic world were still following evolutionary lines that had been long and slow even by geological standards. Take the marine snail *Stegocoelia* in this urn layer, for instance. The genus *Stegocoelia* went back more than a hundred million years, right through the Permian and into the Carboniferous and then the Devonian periods, and over that enormous slab of deep time thrived in the shallow seas of what is now Asia, Australia, North and South America and Europe. Along the way it evolved at least 26 distinct species, from *asakaensis* and *centrosinuata* to *korobcheevonsis* and *turabievoensis*. It will never feature in Hollywood films, or even excite the interest of most fossil enthusiasts, lacking the charisma of a trilobite or an ammonite. But *Stegocoelia* was a solid, durable element of the mid- to late Palaeozoic seas, and tightly and stably bound into the ecological webs of those times. So, we should stay with it in spirit for its remaining ten million years on Earth. It deserves this, at least, for its constancy, before the killing times arrived.

111 (255 Myr)
Claudiosaurus germaini, early reptile
Madagascar

Reptiles were doing well in Permian times. Their invention of an egg as would be understood by a chef of the human species – that is, with a tough outer shell and a food store inside – allowed the young to be born away from water, and the animals to migrate more freely across the land. This character distinguished them from the amphibians, who still needed (and indeed today still need) to stay close to water to breed. However, just to show that nature and evolutionary patterns do not fall into such neat categories, the reptile that builds this urn layer, *Claudiosaurus*, is thought to have kept very close to water, and to have spent a lot of its life swimming through it. This is suggested by its paddle-like feet and a skeleton designed for flexibility rather than strength, where cartilage has replaced some of the bone. One might think of its lifestyle a little like that of the modern marine iguana: living by the shoreline and swimming out to forage in the sea. It's a nice example of an ecological niche, filled in similar ways by different animals – but just a quarter of a billion years apart.

112 (252 Myr)
Powder of the Volcanics, P-T extinction horizon
Meishan, China

The world of the Permian, indeed of the whole of the Palaeozoic, came to an end with a vengeance almost exactly a quarter of a billion years ago. The disappearance of the trilobites, of *Glossopteris*, of poor obscure *Stegocoelia*, and of a host of other animals and plants, had been recognised from the early days of geology. It was the most catastrophic (so far) of all mass extinction events, and left a striking fossil signature in the rocks. But what caused this mass kill? Evidence grew of oxygen-starved, toxic oceans, and of a savage spike in global warming. There was the discovery, too, of a humongously thick, rapidly accumulated pile of basalt lavas that cover much of Siberia. The age when these were erupted matches, exactly, the timing of the end-Permian mass extinction event. Questions of detail, though, remain. Just how quickly were the toxic and planet-warming volcanic gases released? How did the kill mechanisms play out between the land and the sea? What factors determined which species died (most of them) and which lived? There is, too, the question of how closely this ancient release of toxic gases compares with the one we humans are now energetically indulging in: that is becoming an ever more serious question.

TRIASSIC
252-201 MYR

113 (248 Myr)
Trace fossil, *Rhizocorallium*
Thueringen, Austria

This particular fossil recalls one of those horror film scenes when everything looks normal on the surface, but deep down, something is very, very wrong… The end-Permian mass extinction event had certainly been horrific, wiping out more than 95% of the Earth's species. In the seas, that mass kill included an oxygen crisis that simply suffocated most marine organisms. In the aftermath, as oxygen levels returned to normal, one might have expected life to bounce back, as it had done in previous mass extinctions. But this time, on shallow sea floors that looked eminently normal and inhabitable, that didn't happen. Animals were slow to return, and biological communities remained subdued for several million years. Even now, that seems… eerie, and has not been fully explained. In some places, the long-delayed reappearance of *Rhizocorallium*, a common kind of burrow, made by a wormlike animal eating its way across a sea floor, finally shows the ecosystem beginning to properly heal. From now, ecosystems would begin to build properly again (although with very different kinds of plants and animals than before). But what took them so long?

114 (248 Myr)
Ecrinesomus dixoni, ambilobe, fish
Madagascar

When planetary disaster strikes, some weather the storm better than others. In the calamity at the end of the Permian, the world's fish fared better than most, with only modest losses. Perhaps this was partly due to their ability to swim into surface waters, where oxygen levels were higher, while seafloor-dwelling animal communities suffocated in the stagnant waters below. Once the crisis was survived, fish were then well placed within the newly emerging ecosystems, in the long recovery phase that brought in the new biology of the Mesozoic Era.

Paradoxically, this ability to stay clear of danger in life seemed to have helped to petrify their bodies after death, for fossil fish are not uncommon in early Triassic strata. We might here follow the fate of this particular fish specimen, that palaeontologists classify as *Ecrinesomus dixon*i. After a full fishy life, in which it grew to maturity, it died and sank onto a sea floor. There, the lack of oxygen prevented its mortal remains being scavenged and eaten. That carcass lay there, undisturbed, one of many within an extensive fish graveyard, until it became buried, ever more deeply, in sediment. Eventually it transformed, over millions of years, into an exquisite fossil specimen, among millions of its similarly petrified kin. This specimen, of course, went on to make a further, unique transformation, to become part of *Requiem*: a most singular kind of immortality.

115 (248 Myr)
Crinoid stems
Utah, USA

In that devastating end-Permian calamity, some major groups of animals and plants never made it through. The trilobites were terminated completely (though their star had been long waning), as were all the corals, and the reef systems that they formed (the corals did eventually come back from the dead, but that is a mystery for a little higher in the urn). It literally was the end of an era, the Palaeozoic Era, and the start of a new one, the Mesozoic, of which the Triassic Period is the first one-third. A few groups just snuck through the crisis, though, like the protagonist of this layer of the urn, that represents the surviving crinoids (or 'sea lilies'), those stalked relatives of starfish and sea urchins that grew as extensive thickets on many sea floors of the Palaeozoic. Most forms died out – but just one crinoid group survived, that would go on to become the ancestor of all subsequent kinds of crinoid, including those still living today. It is a fine example of an evolutionary bottleneck, for the nature of the survivor must then go on to shape the characters of all the descendants. In this urn layer, the recovery has barely started, but its course has – perforce – been set.

116 (247 Myr)
Australosomus merlei, chondrostean, fish
Madagascar

What can we make of these early Triassic fish, whose ancestors had survived the end-Permian calamity in such relatively good shape? Given this fortunate start, some palaeontologists call them 'disaster species', able to thrive in a devastated seascape. Here is an example, *Australosomus merlei*. It belongs to an ancient group of fish, the chondrosteans, in which some of the bone becomes replaced by cartilage (thus making them lighter). The few chondrosteans still living today include impressively sized fish such as the sturgeon, though *Australosomus* was more at the sardine end of the scale. Nevertheless, this was a predator, albeit a diminutive one, of those early Triassic seas, with sharp teeth on a detachable lower jaw that could shoot forward in a 'stun gun' kind of fashion. So, if a time-travelling visitor were to feel their toe being nipped while taking a paddle on a Triassic shoreline… it might well be *Australosomus*, making full use of an unexpected opportunity to go on a big game hunt.

117 (240 Myr)
Limestone from Tethys Ocean
Israel

Supercontinents, when they form, are so massive that they seem to be endless, permanent features of the face of a planet. But, of course, they carry within themselves the seeds of their own destruction. The moving currents of hot rock deep in the Earth's mantle that brought all of its parts together must eventually act to split this behemoth into fragments once more – often into different fragments from the ones out of which it had originally been built. And so it was with mighty Pangaea. The split that would go on to pull what we now call Africa (plus India) apart from most of Eurasia began. At first, it was little more than a crack in the continent, like East Africa's Rift Valley today. That then widened to a narrow sea, something like the modern Red Sea. And that in turn, over many millions of years, grew into a wide ocean. In the piece of limestone consigned to this layer, we see the beginnings of the life-rich sea floor of the Tethys Ocean, which was to grow to several thousands of kilometres across, before contracting again like some monstrous accordion. Now, there are only its shrunken remnants left, that we call the Mediterranean Sea. In some more millions of years, even that will be gone, and mountains will grow in its place.

118 (237 Myr)
Thamnastrea, yellow coral
Philippines

The fossil record of the corals came to an abrupt halt in what has been called the 'Great Dying' that had brought the Permian Period, and indeed the whole of the Palaeozoic Era, to a close. More than ten million years later, corals returned. These were different corals, though, from the ones that had helped build great reef systems in Palaeozoic times: their skeletons had a different form, and were made of a different kind of calcium carbonate mineral. Their origins are shadowy, for their ancestors may well have lacked skeletons, as in those close coral relatives the sea anemones, and so would have left little imprint on the fossil record. Nevertheless, proper stony corals had finally returned, though it would take another twenty million years or so until their colonies grew large enough to form substantial coral reef structures; nature's recovery from disaster can sometimes be exceedingly slow. These corals – known as the hexacorals or scleractinian corals – are present on Earth still, and have built mighty structures like the Great Barrier Reef. In recent years, though, they have fared rather poorly in human company. Time will tell, all too soon, how well – or whether – they will survive the revolution that is now gathering.

119 (225 Myr)
Rainbow wood
Petrified Forest National Park, Arizona, USA

Arizona's Petrified Forest is one of the great archives of late Triassic times, symbolised by those petrified trunks poking out of the strata in that badland terrain, one piece of which now graces this urn layer. But it is much more than a kind of primeval lumber yard. The particular conditions that fossilised those trees also preserved many of the other forest animals and plants that lived among them. It was a combination of rivers and volcanoes that was key here, as volcanic ash periodically showered down on the river floodplain upon which this forest community lived and died. Silica, percolating out from the fast-weathering ash, captured marvellous detail of the suddenly buried plants and animals, sometimes even down to the level of individual cells. Those classic tree-trunks are mostly of conifers of the araucarian kind (i.e. relatives of the monkey-puzzle tree) that were then abundant, while among them were ferns, cycads, gingkoes. Among these there roamed amphibians and the crocodile-like phytosaurs – and, lately arrived, the dinosaurs, which had appeared a few million years ago and were, for now in very modest fashion, checking out the territory.

120 (220 Myr)
Teleost ray-finned fish
Sahara, North Africa

Triassic times saw the dawn of modern fish – or, at least of the group of fish that is overwhelmingly dominant in today's seas and rivers: the teleosts. The tuna, herring, mackerel and salmon on a fishmonger's slab are all teleosts. If you had fishfingers for lunch, you almost certainly ate a teleost (and the same holds true for jellied eels, if you are so brave). If you fished as a child, the sticklebacks you caught were teleosts, as were the pike you caught as a grown-up angler (while the piranhas that sometimes fish for unwary humans are teleosts too). If you are lucky enough to see a sunfish while snorkelling – well, that's also a teleost, one that can reach a ton in weight. The teleost formula – ray-like fins and tail, light scales, a mobile lower jaw – was one to take over the world, or at least its waters. This was the start.

121 (215 Myr)
Burnt fossil tree charcoal, evidence of ancient forest fires
New Mexico

Forest fires have been a feature of the Earth System ever since there have been forests: sometimes they burned more fiercely, when the atmosphere was oxygen-rich, and so burning is easy, as in those coal forests of the

Carboniferous; and sometimes less so, when oxygen levels dropped. Early Triassic times seem to have been a time of low oxygen levels, perhaps at around half of today's levels. Those low oxygen levels, indeed, may have been one reason why the recovery from the great end-Permian mass extinction was so slow – animals simply found it harder to breathe. The forests seemed to have burned rarely then too, as fossil charcoal fragments from those times are rare. But later in the Triassic, charcoal fragments – like the one here – appear more commonly in the strata, to signal rising oxygen levels and more frequent conflagrations. There are, as ever, wider resonances from such stratal patterns. More oxygen means that animals can have a higher metabolic rate, and be active in ways that were not possible before. It is perhaps no coincidence that the Late Triassic was the time when reptiles, in the form of the magnificent but energy-hungry pterosaurs, first took to the air. These scatterings of charcoal fragments may be signalling a more active world.

122 (215 Myr)
Halorites macer, ammonoid
Timor

This elegantly coiled fossil is, one might say, an almost-ammonite, and is part of a large group of almost-ammonites, the ceratitid ammonoids, that were widespread in the sea in Triassic times (the true ammonites were present then too, but playing a minor part in the marine ecosystems of those days; it would take another biological catastrophe to allow them to take centre stage in the Jurassic). You would have to look closely at a fossil ceratitid to say that was not quite an ammonite: the main difference is that the walls that separate the chambers of the coiled shells are not thrown into quite such extravagantly baroque patterns as in the ammonites. But, the *Halorites* here and its kin would have played much the same ecological role as the ammonites. That coiled shell was wonderfully hydrodynamically shaped, allowing the animal inside to use its jet propulsion system to speed it through the water after prey, that the tentacles and sharp beak would then make short work of. The ancient world of the Triassic was, in respects like these, highly sophisticated.

123 (202 Myr)
Rhaetic Bone Bed
Miscellaneous localities

As the Triassic was ending, the face of the world changed. This change took different forms in different places, but over much of what is now the UK, its expression in the strata could not be more vivid. Below the Severn Bridge, for instance, one may walk and gaze up at the cliffs by the little village of Aust. Most of the cliff is bright red, representing the arid desert conditions of Triassic times. High up the cliff, the strata turn pale grey – that marks the sea lapping up on to land, forming strings of lagoons – and then black, as carbon-rich shales began to accumulate on the early Jurassic sea floor. It is a magnificent example of how rocks are a mirror to environmental change. But look closely at the pale layer (it is too high to reach, so look among the blocks that have fallen from the cliff top). Within it, there is a curious black-speckled layer, just a few centimetres thick. Examine it, with a magnifying glass, and the speckles become lustrous, and take the form of scattered teeth, scales and vertebrae of fish (and, if you are lucky, of a fragment of ichthyosaur or plesiosaur). It is a bone bed – probably not the result of some local catastrophe (as was once thought), but simply a serendipitous current-sweeping together of the dense bony fragments, as the sea came in to encroach on the land. It is just a microcosm of a wider landscape undergoing transformation – but very fitting to capture within the urn, nonetheless.

JURASSIC
201-143 MYR

124 (195 Myr)
Oxynoticeratidae, ammonite
Madagascar

Fossil ammonites elegantly symbolise long-vanished Jurassic seas – and have caught people's eye long before the realisation that there was such a time as the Jurassic, when very different kinds of life ruled the Earth. In Roman times, Pliny the Elder called them 'horns of Ammon' after the ramshorn-headed Egyptian god, and that name was still being used by the savants of the eighteenth century, who puzzled over the meaning of these stone-encased spiral shells. At that time, too, these beautiful petrifactions, which could be picked from the crumbling cliffs of Lyme Regis in Dorset, were sold to passers-by by a young, dirt-poor girl called Mary Anning. From this, it is said, came the tongue-twister 'she sells sea shells by the sea shore'. This young girl was to grow into 'the greatest fossilist the world has ever seen' (though always remained impoverished), as she hauled ever larger and more astounding remains from those cliffs. The saurian monsters so unearthed now take most attention, of course, but the ammonites once sold for pennies continue to prove their worth. They now provide a genuine time machine, one that can allow Jurassic strata to be split into some 70 time-slices (or biozones as they are more technically known) based on ammonite dynasties, each one representing a particular evolutionary stage. It's a marvellous palaeontological chronometer.

125 (193 Myr)
Golden pyrite, *Crucilobiceras*, ammonite
Dorset, England

Most ammonites in Jurassic strata are crushed flat by the weight of all the overlying rocks. The most elegant ones, though, are preserved in their original three dimensions, especially those that are preserved in the 'fool's gold' of pyrite. This kind of petrifaction is the result of a particular kind of chemistry of the sea floor, on to which the spiral ammonite shell sank after the death of its molluscan occupant. If that sea floor is *just* at the boundary between the oxygenated realm of the waters above, and the anoxic realm of the stagnant (and smelly) muds below, then iron and sulphur from the water can combine to form pyrite within the shell itself, the reactions aided and abetted by the decaying tissues of the deceased animal – so quickly, indeed, that the pyrite forms a tough internal reinforcement that is subsequently nigh-well impossible to squash flat. It's a most beautiful as well as effective form of petrifaction – though, ironically, the shell itself is often dissolved away afterwards. A little like filling a house with concrete, and then removing the walls and roof, it gives a very particular view of the architecture of this iconic Jurassic fossil.

126 (190 Myr)
Devil's Toenail, *Gryphea*, bivalve
UK

The 'devil's toenail' is such an apt name for this fossil and likely goes back many centuries (it would be an impressively large devil too, for *Gryphaea* can be several centimetres long). It's the most hard-wearing of fossils, too, easily rain-washed out of the Jurassic shales (and often retaining its shape even after having been transported by the glaciers of the ice ages, to find a new geological home encased within boulder clay or glacial gravel – which can be among the best hunting grounds for these fossils). It is one of the most visible signs of the slow evolutionary ascendency of the bivalve molluscs (i.e. clams) as 'sea shells' in the Mesozoic Era – though it doesn't play by normal bivalve rules, which is exactly what gives it its devilishness. In normal bivalves, the shells are essentially mirror images of each other, but in *Gryphaea* one of the pair of shells enlarges and curves around – just like an ingrowing toenail – to which the other one becomes a lid. Non-standard, perhaps, but very effective as a means of finding the right shape to 'float' on the muddy sea floors common in those days.

127 (185 Myr)
Cycad frond
Talkeetna Mountains, Alaska

If you are a gardener, you may have been tempted by advertisements to create a Jurassic garden by planting a cycad – a Sago palm, or such, say – as the Jurassic has often been called the 'Age of Cycads'. Well, that may be stretching it a bit, but cycads were certainly a good deal more common in that period of geological time than they are today. Climate probably had a little to do with this, as cycads today are tropical to subtropical plants, and the Jurassic was generally more of a warm greenhouse world than is today's (though another few decades of burning fossil fuels will set us well on the way to getting back, if rather suddenly and brutally, to that planetary state). That being as it may, cycads haven't evolved greatly since those days, so it is fair to say that you can acquire one as a living fossil to grace your garden. Cycads do look quite palm-like, though they are only rather distantly related to palms, bearing neither flowers nor fruit. Today, alas, cycads are doing rather poorly, with several species on the brink of extinction.

128 (183 Myr)
Jet
Whitby, UK

When Queen Victoria was in mourning for her beloved Prince Albert, one expression of her loss was in jewellery. The seaside cliffs around Whitby in Yorkshire had long yielded fragments of a kind of coal, locally called jet, which took on a lustrous sheen when polished. It was the ideal ornament for a grief-stricken monarch, and started a craze for this peculiar black mineral which has now subsided, but never really gone away. Jet is a kind of fossilised wood that occurs in a layer of dark Jurassic shale called the Jet Rock which, in various guises, occurs all around the world. Now closely studied by geologists, its even more peculiar chemistry shows that it marks a time when the atmosphere was suddenly (and naturally) enriched in some combination of the greenhouse gases carbon dioxide and methane. What has been called a hyperthermal event ensued, when global temperatures soared by some five degrees Celsius, oceans stagnated, and some forms of life went extinct while others thrived. Much of the reason why the Jet Rock is now so closely scrutinised is that we humans appear to be on the brink of precipitating a similar hyperthermal event.

129 (175 Myr)
Annelida, *Serpula*, worm
Poland

It doesn't look like much of a fossil: just a small limy tube, rather untidily coiled. And, indeed you can go to a beach today and pick up dozens of their modern equivalents, usually as encrustations on sea shells. The animal inside the tube, now, is a different story, especially if you see it in life, and in action. It's a worm, but not one that eats mud, like the ones in your garden and many on the sea floor. Instead, it has a beautiful fan-shaped array of fine tentacles that it uses to catch microscopic plankton out of the water. These are worms that know their place – and indeed are adept at finding the best place from which to do their own graceful and highly effective kind of fishing. You can sometimes find serpulid worm tubes encrusting on fossil ammonites – and these are commonly found on the leading edge of the ammonite's spiral shell, to have been neatly positioned in the nutritious slipstream of that animal as it swam.

130 (170 Myr)
Ostrea
Peru, South America

A familiar friend often turns up in the Jurassic – and indeed, all the way from that time (and a little before) to the present day. It is *Ostrea*, a kind of edible oyster. It can be so common that its thick shells may stack up to form a rock layer in their own right, and a geologist soon learns to recognise the distinctive prismatic structure of these kinds of shells under the microscope. The shells, moreover, can be so finely preserved that very precise chemical analysis of the shell layers can show how temperatures and salinity of the sea water changed from season to season, and comparison of many oyster shells through different levels of strata can show how climate changed across millions of years. There is even an old record of fossil pearls associated with some petrified *Ostrea* of the Jurassic. Sadly, though, most fossil pearls, through the ravages of time and long burial, have lost their wondrous lustre.

131 (169.5 Myr)
Megateuthis gigantea, belemnite
Germany

The belemnites are such distinctive, cigar-shaped fossils that it is little wonder that the ancient Greeks thought them to be javelins hurled by the gods from the heavens during storms. The truth is almost as strange, as these solid, crystalline limy structures acted as counterweights within squid-like animals to help them swim more effectively.

Usually they are the only part of the animal found fossilised, and the specimen in this urn layer, *Megateuthis*, was one of the largest ever to have evolved, some reaching almost half a metre long (and so worthy to be weapons wielded by Greek gods during their stormy confrontations). On very well-preserved specimens, one can sometimes find belemnites associated with arrays of little hooks, that would have been originally on the animal's tentacles. And, on rare *exceedingly* well-preserved specimens the fossilised ink sac can be found too, and it has been a party trick since the times of the great Victorian geologists to remix this Jurassic ink with water, and then to paint with it – sometimes to use it to try to draw reconstructions of the belemnite animal itself.

132 (167 Myr)
Cetiosaurus, early sauropod dinosaur
Oxford, UK

In Jurassic times, the dinosaurs finally began to bestride the world stage in fittingly majestic manner – once the end-Triassic mass extinction had cleared the way for them, that is, by devastating the up-till-then-dominant synapsid reptiles, to make way for dinosaur ascendancy. *Cetiosaurus*, a bone of which now lies in the urn, has its own part of that history, though it became rather a tangled part once human palaeontologists got involved. It was the one of the first dinosaurs to be described, in 1841, from fossil bones excavated near Oxford. The powerful and controversial Sir Richard Owen, first Director of London's Natural History Museum, named it – though as a marine reptile ('whale lizard'), not a dinosaur. That's excusable, as the bones were found in marine Jurassic strata – the carcass we now know having been washed in from a nearby Jurassic landmass. And, as Richard Owen himself only established the dinosaurs in science the following year, they officially didn't exist then! Still, *Cetiosaurus*, once settled as part of the dinosaur family, is quite a handsome representative. It was an early sauropod – they of the great bulk, long necks and long tails – although at up to 16 metres long and three metres tall, not as massive as some that were to come.

133 (163 Myr)
Belemnite, squid-like cephalopod
Mikhailov Ryazan, Russia

Fossil belemnites may have a smooth, bland-looking surface, but invisible stories are hidden within them, that betray the patterns of their lives. Break a belemnite and the first thing you will see is the radial patterns of the tiny calcium carbonate crystals which make them up, like the spokes of a wheel. But look more closely, with a microscope, and you can see fine concentric rings, a little like miniaturised versions of tree-rings, superimposed upon these radial spokes. They are indeed like tree-rings in that they represent the growth of this singular kind of skeleton, and there are very many of them – a study counted some 600 in one specimen. They are thought to represent daily growth layers (modern cuttlefish shells have similar very fine daily striping) and show that belemnites had relatively short lives, of a about a year and a half in this case – and so quite similar to the brief but interesting lives of modern squids and cuttlefish. Furthermore, chemical patterns in the layers of that belemnite did not pick up strong seasonal patterns, hinting that that animal lived and ate in relatively stable deep waters.

134 (160 Myr)
Araucaria mirabilis, pine cone
Patagonia, Argentina

It was the site of a disaster: an entire forest was felled by a mighty volcanic eruption, the trunks and debris then being swept into piles by flooding river-waters. 160 million years, now exposed by erosion on the windswept badlands of Patagonia, it has become one of the world's classic fossil forest sites. Most of the now-petrified logs are of the conifer *Auracaria*, a relative of today's 'monkey-puzzle' tree, and these grew to spectacular size, reaching to a hundred metres in height. Many of the pinecones here are beautifully preserved, with petrified seeds still inside them, while some of the bark still has the marks of being chewed by Jurassic equivalents of today's bark-beetles. These *Auracaria* forests formed part of Jurassic landscapes worldwide, and it has been speculated that the giant sauropod dinosaurs of those days would have used their long necks to reach up and browse upon that high auracarian foliage.

135 (160 Myr)
Radiolarite, sedimentary rock recording the closure of the ocean
Corsica, France

In doing geology, one can climb to the top of a high mountain, and find oneself at the bottom of a very deep ocean. As a bonus, one can swim – in spirit, of course – in the surface waters of that ocean at the same time. In those sunlit surface waters of Jurassic times, there thrived the radiolarians, microscopic protozoans that had (and still have, for these organisms still exist today) skeletons of silica of matchless complexity and beauty. After the death of these tiny single-celled animals, their baroque skeletons slowly settled through water that was perhaps five kilometres deep, to eventually land in the abyss, forming layers of silica-rich ooze on the floor of the wide Tethys Ocean. These oozes, soon hardened into layers of tough chert, were later scrunched up to form part of the growing Alpine mountains, as Africa inexorably moved ever closer to Europe. The two crustal masses are still on a collision course, and the remains of the Tethys Ocean, that we know as the Mediterranean Sea, are destined to be converted into that mountain belt too as it grows. *Sic transit gloria mundi* – though only to produce further planetary wonders.

136 (153 Myr)
Diplodocus, sauropod dinosaur
Morrison Formation, North Wyoming, USA

Dippy the *Diplodocus* in Pittsburgh's Carnegie Museum is likely the world's most famous dinosaur – and therefore the most famous fossil of any kind, of course. It is certainly (by proxy) the best-travelled, as Andrew Carnegie made plaster casts of this mighty sauropod skeleton and sent it to heads of state around the world, in a nice display of dinosaur diplomacy. It's a deserved accolade. *Diplodocus* is no longer the largest land animal ever to have lived (that mantle has now passed to *Argentinosaurus*) but, at more than 30 metres nose-to-tail, and likely weighing in at approaching 15 tons, it remains most impressively monstrous. How did – how *could* – such a beast have lived? It's a question that has exercised many palaeontologists. Did it need to live in water to support its massive bulk? That idea was once popular, but now seems unlikely – *Diplodocus* seems emphatically to have been a land animal. How did it protect itself, as a herbivore with a tiny skull and feeble teeth? Well, its sheer size would have put off most predators, and it may have been able to lash its long tail – or perhaps even crack it like a whip. Even keeping itself supplied with oxygen is a problem at that size, and so a stout heart and efficient lungs must have been part of the package. Palaeo-engineering calculation shows that it may have been able to balance itself on its hind legs and tail, and rear up to 11 metres or so in height.

137 (152 Myr)
Pliosaur paddle bone, marine reptile
Weymouth, England

That extraordinary, self-taught 'fossilist' Mary Anning unearthed the first near-complete skeleton of a plesiosaur in Lyme Regis in 1823. She was then 24, and already a pioneering veteran of these explorations (with the first excavated ichthyosaur already to her credit, when she was still in her teens). The most distinguished anatomist of those days, Baron Cuvier, took a long time to be convinced of the reality of this creature with its large body, long neck and bony paddles, finally pronouncing it 'altogether the most monstrous animal that has yet been found in the ruins of an ancient world'. The pliosaurs, an offshoot of the plesiosaur lineage, would have further amazed the celebrated baron, for although the neck was shorter, the crocodile-like head with its array of large, sharp teeth was yet more massive than in typical plesiosaurs, reaching two metres or more in length. These charismatic creatures are often lumped with the dinosaurs, but they are marine reptiles, not dinosaurs – and indeed the pliosaurs likely ate any dinosaurs unwary enough to come within their range.

138 (152 Myr)
Ichthyosaur, giant marine reptile
Europe

Animals with backbones came on to land just the once, with the land-conquering odyssey of that 'fishopod' *Tiktaalik*, back in Devonian times. That evolutionary journey, to which we owe our own human lives, was never repeated. But there have been many invasions back to the sea from the land. In this layer of dust is symbolised one of the first of these reverse evolutionary journeys: a representative of the ichthyosaurs, those dolphin-shaped marine reptiles with their saucer eyes that played such a large role in the Jurassic seas. Earlier, in the Triassic, its ancestors were terrestrial reptiles living by the shore and venturing ever farther out to sea to catch fish; over millions of years, the legs transformed to paddles, the backbone stretched into a tail with a fin, bone density changed, and the whole body became more streamlined. At much the same time, the long-necked plesiosaurs were making a similar journey into the sea. Something like thirty more waves of invasion of the sea were to follow over the next 200 million years, including turtles, whales, seals, penguins: the call of the sea is clearly an insistent one.

139 (146 Myr)
Saccocoma, crinoid, 'swimming sea lily'
Germany

The Solnhofen Limestone of Germany – a limestone so fine and evenly layered that it was used for printing in lithography – has long been one of the world's iconic fossil localities. Most notoriously, because of the 19th century discovery within it of a fossil feather – and then of a whole fossilised part-bird, part-dinosaur. *Archaeopteryx* is still part of the chain that links birds to dinosaurs (and indeed these days birds technically *are* dinosaurs). Other extraordinary fossils have come out of Solnhofen – marine reptiles, and the fantastical 'death march' fossil tracks of a horseshoe crab, with the petrified crab at the end of it, that marks that doomed animal's last steps before it succumbed to the toxins of that Jurassic lagoon. But go fossil-hunting among the large spoil-tips of the Solnhofen quarries, and you'll likely be disappointed. These marvellous fossils are rare – except for one kind. Many of the limestone slabs bear the remains of a small stem-less crinoid (or 'sea lily') with its thread-like arms. Did this animal, *Saccocoma*, somehow manage to live in the deadly Solnhofen waters of Jurassic times, or was it washed into the lagoon in its billions by storms from the open sea, to be quickly overcome by the poisonous waters and then entombed in the sediment? It's a tricky question, still – but a most thought-provoking enigma.

CRETACEOUS
143-66 MYR

140 (124 Myr)
Iguanodon vertebrae, dinosaur
Isle of Wight, England

Iguanodon was almost the first dinosaur to be scientifically named and described, by that remarkable physician, Gideon Mantell, whose once-successful medical practice suffered, and marriage foundered, through his passion for this new kind of Victorian science. *Iguanodon* and Mantell were beaten to this honour, by a whisker, by that most omnivorous savant of those days, William Buckland (who claimed to have eaten every kind of animal then known, though confessed to not enjoying bluebottle much) and *Megalosaurus*. Nevertheless, *Iguanodon* is a classic dinosaur and Mantell was a fine scientist, who was closer to the truth in reconstructing it than some of his eminent colleagues. The early studies show, too, the perils of palaeontology, par excellence a subject where incomplete data is fitted together as reasonably as seems possible. A spike-like bone was left over in those early reconstructions, and so was put on the end of the nose, rhinoceros-style. It later turned out to be the thumb, likely adapted to strip vegetation off branches in this vegetarian saurian. A mistake, for sure, but a most charming one. And one can still follow in the footsteps of *Iguanodon*, here and there – literally, for its footprints can sometimes still be found among the sandstones that were once swamp deposits of Cretaceous times in the Weald and Isle of Wight.

141 (121 Myr)
Ephemeropsis trisetalis, mayfly larvae
Liaoning Province, China

One of the characteristics of past geological times is the juxtaposition of the strikingly alien – those monstrous Cretaceous dinosaurs, for instance – with the familiar. In this case, some of those vanished landscapes hummed with mayflies. These most delicate of animals can sometimes be fossilised, though not so much the briefly living adults as their larvae; and, in studying these, one can learn much about how fossilisation itself takes place. The deposits of an ancient Cretaceous lake at Jehol, in China, amid larger and more spectacular beasts such as dinosaurs and pterosaurs, abound in tiny, exquisite fossil mayfly larvae. Peering closely at these, it was found that some are completely flattened from the weight of overlying strata, their delicate exteriors beautifully preserved as carbon films, though with nothing left of their internal organs. Here, it seems that, lying on a lake floor with little oxygen, these minute carcasses took on a dusting of clay particles that slowed external decay while, inside them, microbes could work unhindered to eat through the soft tissues. Inside some of the larvae bodies, though, the 'fool's gold' of pyrite crystallised soon after death, to preserve them in three dimensions. Biologically, these organisms may have been dead and buried. Within and around them, though, a kind of subterranean geological life continued.

142 (117 Myr)
Coral
Spain

After the end-Permian and end-Triassic mass extinctions, when corals suffered so grievously and coral reef systems disappeared, the Cretaceous was a time when the new kinds of coral could thrive. Perhaps, though, the word 'thrive' needs to be used carefully. For, while fossil corals are common in Cretaceous strata that represent shallow sea floors, and these are of the same general kind as the fossils that live today, for the most part these did not build up into the kind of huge reef structures that we are familiar with. Rather, they built small, scattered communities on the sea floor, amongst other kinds of organism. What held them back? One factor here may have been climate: the Cretaceous world was a greenhouse world, with little or no polar ice, high levels of carbon dioxide in the air, and warm to hot conditions pretty much worldwide. Perhaps, in such conditions, the corals could not thrive sufficiently to build enormous reef structures. Other organisms did form reefs in those times and in those conditions, but it is yet another reason to look soberly at what is happening to coral reefs today, as the world warms.

143 (117 Myr)
Raphidonema contortum, Lelapiidae, sponge
Oxfordshire, England

While living organisms have evolved into an ever more remarkable array of new forms over the past half billions, others have simply carried on largely unchanged with tried and tested recipes for life of the simplest kind. The sponges, for instance, date back more than half a billion years – much more, if a recent record of a fossil sponge in 890-million-year rocks in Canada turns out to be true (that would make them the oldest animal by some 300 million years). Be that as it may, the sponges have carried on blithely doing their stuff, which is attaching themselves to the sea floor and filtering the seawater for tiny food particles. And here they are in the Cretaceous, courtesy of a remarkable deposit called the Faringdon Sponge Gravels. In this, the calcium carbonate skeletons of the sponges remained standing on the sea floor for years after death, becoming infiltrated by mud particles. Becoming thus 'pre-fossilised', they were then broken up by marine currents and washed into submarine gravel masses, in the strata of which they can still be found now. If it seems a little cruel to crush one of these beautiful sponges into a layer of this urn, think of the fate that many of these fine fossils suffered in years past: broken up as surface material for roads. Now that really was a scandal, for the veteran animals of the Earth.

144 (113 Myr)
Orthopterida, grasshopper
Brazil, South America

It's good to see another familiar face, as we explore the Cretaceous world through the lens of this artwork. It's a grasshopper, courtesy of another calm lake with toxic bottom waters that acted as a pickling jar for any organisms that fell into it. This particular lake now forms the strata of the Crato Formation in Brazil, set on the Araripe Plateau, a setting that brings to mind the Lost World of Arthur Conan Doyle. Grasshoppers, now, have lived on Earth since the coal-forming swamps of Carboniferous times, and so were already ancient when they lived around the Crato lake. But if we were to listen hard, would these particular examples be quite familiar? Or would something be missing? Sound does not fossilise (at least not until humans started to preserve it on magnetic tape and vinyl discs) and so no grasshopper chirp has ever left an impression on ancient strata. But the means by which grasshoppers chirp – specialised noise-making structures on their wings – can sometimes be fossilised. Now, this is something of a niche study within palaeontology, but the evidence so far suggests that grasshoppers only evolved these chirp-making structures after Cretaceous times – and if so, our witness that lies here was mute. This particular grace note, within the infinitely polyphonic song of the Earth, was still to sound.

145 (113 Myr)
Rhacolepis, Elopiformes, fish
Brazil, South America

The Cretaceous fish *Rhacolepis* is a fossil with a heart. Quite literally so: for it is another instance of extraordinarily high-fidelity preservation from the fossil-rich layers of Brazil's Araripe Plateau. The fish here, likely killed by salinity changes in an arm of the Cretaceous sea, were so well preserved in those sea floor sediments that they show not only soft tissues, but also the bacteria beginning to decay those tissues, petrified before they could finish rotting the carcass. One hundred and thirteen million years later, one can take one of these long-dead fish and X-ray it, to reveal the internal structure of the fossilised heart, including its chambers and valves. The *Rhacolepis* heart turned out to be a long-lost cardiac 'missing link', between the hearts of primitive fish and of modern bony fish. Charles Darwin would have been pleased, to see the pulse of evolution so neatly measured.

146 (105 Myr)
Siroccopteryx marocensis, pterosaur teeth
Morocco

When that most remarkable of pioneer palaeontologists, Mary Anning, extracted a fossil pterosaur from the dangerously unstable cliffs of Lyme Regis, the anatomist Baron Cuvier, already astonished by the plesiosaur that she had found earlier, now gave the 'palm of strangeness' to this 'monster half vampire, half woodcock, with crocodile's teeth… and scale armour'. The pterosaurs, that ruled the skies from Jurassic times right through the Cretaceous, were certainly a unique means for animals to take to the air. Their wings represent a quite different type of engineering to those of birds and bats, in that the main strut is a single, enormously extended fourth finger that carried the sail-like wing membrane. The baron was mistaken in one respect, though: the pterosaur body was generally coated with soft fibres, more fur-like than feathery, rather than scale armour. The *Siroccopteryx* that gave its tooth to this urn was a magnificent beast, with a wingspan that approached three metres. Some of its relatives, mind, like *Arambourgiania*, reached wingspans of nine metres. This truly was a time of giants.

147 (105 Myr)
Trigonia aliformis, bivalve
Wyoming, USA

Amongst all of the monsters and giants of Cretaceous times, it is sometimes a relief to turn to the small fry, the kind of shelly fossils likely to be encountered by a fossil-hunter in rock crags and quarries. *Trigonia* is a fine example, for although it is one of – by then – many kinds of bivalve mollusc that had evolved, it is also one of the most distinctive, with a thick shell ornamented by a characteristic set of ridges. Different members of the *Trigonia* family successfully inhabited shallow seas for a long time, first appearing in Triassic times and then ranging through the Jurassic and Cretaceous, when they seemed to disappear – until a *Trigonia* (now called *Neotrigonia*) was pulled from the sea floor off New Zealand. A genuine living fossil, then, if living a good deal more reclusively than in its prime.

148 (105 Myr)
Oyster
Walnut Formation, Texas, USA

What was life like for an oyster in the Cretaceous? Well, it could be a pretty tough one. A little more than a hundred million years ago, oysters lived in a shallow sea, not far off the low-tide mark in what is now Texas. They prospered well enough to build small reefs, their thick shells piling up to make mounds a few metres high and a few tens of metres across (which we now see as limestone beds). Look closely at these shells, though, and some of the day-to-day troubles in an oyster's life are revealed. Very many of them have holes in them, drilled by a whole variety of organisms that either wanted to excavate themselves some living space, or help themselves to some fresh oyster. In the Texan oysters, the range and size of these predatory drill-holes suggested that the culprits included other kinds of bivalve (acting the way 'ship-worms' act today), and kinds of sponge, worm and barnacle adapted to this lifestyle. There were holes made around them, too, as crustaceans, worms and sea urchins burrowed through the sea floor. Even for creatures as tough as an oyster, the foundations of life must sometimes have seemed a little precarious.

149 (100 Myr)
Sea urchin
Madagascar

Sea urchins, those animals that one tries to avoid when paddling in the sea – for their sharp spines can inflict a nasty wound – have played a large part in the study of the world of the Cretaceous, and indeed in establishing wider principles about the living world of this planet. They are rather extraordinary animals, though their name itself is a fossil, its meaning stranded by linguistic evolution. 'Urchin' used to mean hedgehog in old English (coming from the old French world 'heruchun', which itself has evolved to 'hérisson'); so 'sea hedgehog' suits its spiky nature much better! This formidable defensive battery is dual purpose, as some sea urchins walk on their spines, while they also have soft, highly mobile tube feet operated by a unique hydraulic system, an outrageously baroque five-toothed jaw called an 'Aristotle's lantern', and a skeleton of which each element is shaped – no matter how complex in shape – out of a single crystal of calcium carbonate. It is the kind of animal structure that one would not dream of designing from scratch, for it's too crazy by far. Crazy, perhaps, but successful too: sea urchins are still with us today, in large numbers.

150 (97 Myr)
Ceratodus tooth, lungfish
Kem Kem Formation, Morocco

Even in a fast-changing world, some things stay much the same. Lungfish had appeared way back in Devonian times, and we met one quite a few urn layers ago, in a Carboniferous swamp rock. Two hundred million years later, here is another member of that most conservative family (and, of course, they are still with us today, splashing in swamps and burying themselves in mud, while jet planes roar overhead). To give this layer an extra touch of eccentricity, we have here the 'tooth of a horned tooth', for *Ceratodus* is from the Latin meaning 'horned tooth'. Indeed, lungfish teeth are a quite unique addition to the vertebrate dental armoury. Looking rather as if they had been constructed by one of the more inventive origami enthusiasts, they are made of a set of ridges that extend across the palate and jaws, though unlike normal teeth the pointy parts are arranged outwards and not vertically. Unusual, perhaps, but they have helped lungfish keep themselves well-fed for an unimaginably long time.

151 (97 Myr)
Scombroclupea diminuta, fish
Lebanon

Several ancient fish have been laid to rest in *Requiem* so far, and by and large the 'ancient' pattern of these charismatic fossils has been all too obvious. Many have been heavily armoured, with thick bony plate or lustrous scale, or had strange appendages: the kind of things that would surely scare off the customers if placed on a fishmonger's slab. Here, now, on the slab of Late Cretaceous limestone that has transmuted into this artwork, there is the skeletal outline of a fish that looks almost comically familiar. About the size and shape of a sardine, one doesn't see scales – these were too thin to fossilise – but just vertebrae, ribs, fins and head. One might imagine it sketched in a child's cartoon, next to a cat licking its lips. *Scombroclupea* was part of the great expansion of 'modern' ray-finned fishes that took hold of the oceans and – so far – have not let go.

152 (95 Myr)
Hemiaster lusitanicus, sea urchin
Portugal

Hemiaster is another of the kinds of sea urchins which flourished in the chalky oozes of the Cretaceous sea floor, and it is still with us today, though less abundantly than in its heyday of those extensive warm seas. Indeed, it is hard to find or examine today, even if you were to visit its home territory with aqualung or snorkel, for it burrows within the sea floor muds, ten centimetres or so below the sea floor, keeping connection with the seawater above only by a narrow vertical shaft maintained by its busy tube feet. This reclusive urchin lives by feeding on organic detritus in the muds, a soft diet for which it does not need the powerful and complicated jaw apparatus of the Aristotle's lantern. It is, indeed, one of the few sea urchins to have wholly lost this extraordinary apparatus in the course of their evolution, much after the fashion of cave animals that have lost the sense of sight.

153 (93.9 Myr)
Strata of the Bonarelli Anoxic Event
Furlo Gorge, Italy

What happens when an ocean suffocates, through over-heating? In the Chalk strata of Europe, the effect is seen in, literally, black and white. The Chalk strata are normally dazzling white petrified deep-sea oozes, the remains of countless algal micro-skeletons. Looked at closely, they show abundant signs of riotously prolific life: countless burrow-traces, and fossils of oysters, sea-urchins and much more. But, here and there, the strata turn black, organic-rich, and the signs of sea floor life disappear. These are now seen to represent worldwide 'Oceanic Anoxic Events', when the oceans heated up, stagnated, acidified and the sea floor suffocated. This particular example is from strata of the 'Bonarelli Anoxic Event' in Italy, at the boundary between the Cenomanian and Turonian Ages of the Cretaceous Period; this urn layer includes examples of both the living and dead sea floors. The pattern of death rippled outwards: at this level, all the pliosaurs died out, most ichthyosaurs, and many sea floor and microplankton species too, the plankton being thought to have succumbed to ocean acidification. The culprit? – there are chemical signs in the strata of increased volcanism, that would have loaded the atmosphere with carbon dioxide, with recovery to normal climate conditions taking nearly half a million years. The parallels with the global warming now beginning (caused by humans, not volcanoes) are all too clear.

154 (93 Myr)
Vascoceras glabrum, ammonite
Nigeria, West Africa

It is one more ammonite of the many that swarmed in the seas through the 130-million-year span of the Jurassic and Cretaceous. *Vascoceras* has a neat spiral shell that looks as though it could have cleaved easily through the water, and so is thought to have been an active predator. But what of *glabrum*? It is one of at least 25 described species of *Vascoceras*. Now, these are long-dead fossils, so one can't use the standard test of a species (as members of an interbreeding population). Rather it has (in the mind of an ammonite expert, at least) to have a distinct shape, being what palaeontologists call a morphospecies, the only concept that works when all one has to go on is the fossilised skeleton. And every morphospecies has to have a single reference specimen – a type specimen. In the case of *glabrum*, it is the specimen labelled BMNH C 47703, for which one could trot down to London's Natural History Museum to politely ask to see. It is the gold standard for recognition of that species.

155 (87 Myr)
Oldest island on Earth: agate
Madagascar

Madagascar has ploughed its own furrow on the Earth for a long time. It split from East Africa about 150 million years ago, as part of a larger continental fragment. Then, about 90 million years ago, this crustal block drifted across a hotter mass of the Earth's deep mantle. Amid huge volcanic eruptions, it broke up once more, releasing a part of it that we now call the Indian subcontinent to take its long journey to ultimately collide with Asia and raise the Himalayas. Meanwhile, Madagascar was left behind in isolation, a crucible for the evolution of a unique – though now threatened – flora and fauna, including lemurs and, until not so long ago, the giant bird *Aepyornis*. This layer finds home to a mineral-filled gas bubble from within lava erupted in that second breakup. It is a reminder that Madagascar today is still volcanically active, which is puzzling, as by now it should be quietly sitting in a tectonically peaceable zone of the Earth. The latest idea – after much patient probing of the way seismic waves pass through Madagascar's rocky foundations – is that a fragment of Madagascar's dense and (relatively) cold lower crust is peeling off and sinking into the mantle depths below, allowing hotter mantle to rise up and generate those volcanoes. It's suspected to be a delayed response, still, to that 90-million-year-old breakup – and so a measure of cause-and-effect, on a planetary scale.

156 (85 Myr)
Xiphactinus premaxilla, bony fish
Kansas, USA

Xiphactinus, sometimes known as the X-fish, is a reminder that not all the top dog monsters in the Cretaceous seas were marine reptiles. Powerfully built, with wicked teeth and up to five metres long, this bony fish could more than hold its own even in those dangerous waters. One recently found specimen had the paddle of a mosasaur in its jaws, to show the level of its ambitions, while another famous specimen was found with another whole fish almost half its size in its stomach, the predator in the case likely succumbing to its own voracity, as the victim thrashed inside it. Fatal greed, in this case, but it did not prevent *Xiphactinus* from being successful worldwide for some fifty million years. It would take an even bigger monster, one that came from outer space, to kill it off.

157 (85 Myr)
Conulus albogalerus, echinoid
Kent, UK

When Charles Darwin wrote *The Origin of Species*, he assembled many pieces of evidence in support of his theory that organisms changed through time in what he called 'descent with modification' (he himself rarely used the term 'evolution') through natural selection. He did not cite fossils as evidence, though, bemoaning what he saw as the very patchy record of the life they represented, like a book with most of the pages torn out. At the time, that opinion seemed justified, as the systemic description and cataloguing of the enormous storehouse that is Earth's fossil record had barely begun. But still, it is a pity that he did not look closely at the rocks beneath his feet where he lived, at Down House, where they are beautifully displayed in the Kent cliffs, not too far away. The fossilised echinoids (that is, sea urchins) within the Chalk strata of those cliffs were to yield – once they had been closely and painstakingly examined – one of the finest and most convincing examples of evolution captured by petrifaction. The echinoid represented here, *Conulus*, was not one of the superstars of this story (we shall meet one of those in a few layers' time). Nevertheless, with its high cone shape and flat base, it was neatly adapted to a life moving across the sea floor. It had found its niche, within the tree of life.

158 (80 Myr)
Araucaria, monkey puzzle tree
Madagascar

By Cretaceous times, the *Araucaria* tree would have been on the road to nowhere on Madagascar. A hundred million years previously, in Triassic times, it had thrived when Madagascar was but a small part of the Pangaea supercontinent. Now, as Madagascar was splitting away from Africa, this tree formed part of a biological experiment that was beginning on this large island, as evolution produced new lines of plants and animals in this stranded new ecoregion, and eliminated others. *Araucaria*, generally in decline as competitor trees appeared, hung on in some parts of the world – South America, Australia, New Guinea – but disappeared in many others, Madagascar included. Now, of course, with human help, it is coming back as part of the gigantic, unique merry-go-round of species that we have set in motion, and that will reshape Earth's biology for all time to come. There is probably an *Auracaria* in a garden near you, and likely there are some now in gardens in Madagascar too.

159 (80 Myr)
Segnosaur dinosaur egg
China

Segnosaurus was one of the mostly-carnivorous theropod group of dinosaurs, and indeed had something of the shape of a smallish *Tyrannosaurus* – except when one looks at the head, which has much smaller in proportion, with smaller and blunter teeth. This kind of dinosaur had evolved to become a herbivore, and so was generally inoffensive (other than to plants, of course) by comparison with its ferocious kin. It was likely a social animal too – and also somewhat nomadic, for its eggs were laid in collective nesting sites that apparently changed in location from season to season, as the egg-containing layers seem to represent individual breeding events, and show no evidence of re-occupation in succeeding seasons. It's the kind of detail that gives a glimpse into the domestic routines of the dinosaurs.

160 (80 Myr)
Micraster, echinoid
Spain

We meet here a superstar of biological evolution, which had lain hidden in the Cretaceous strata of southern England, even while Charles Darwin was complaining of the poverty of the fossil record. Well, the fossil record is rich far beyond Darwin's dreams, but at the time the hard work had not yet been done to uncover it. The superstar is a humble sea urchin, *Micraster*, the skeletons of which are common in Chalk strata. Its secrets were uncovered by a couple of those indefatigable amateur naturalists who were springing up in late Victorian times, Arthur Rowe and Charles Sherborn. They devoted their free time over several years to 'fairly skinning' those cliffs of their fossil *Micraster* ('I pity the next collector', wrote Sherborn), and then painstakingly measuring thousands of specimens to see how they changed over a few hundred metres thickness of Chalk strata (and what we now know to be about ten million years of time). These little heart-shaped urchins did indeed change, to better adapt to their lifestyle of burrowing through the chalky oozes: their shape became more arched, they broadened, the position of the mouth moved forwards. They changed so imperceptibly one into another, moreover, that it was impossible, Rowe grumbled, to say where one previously named species stopped and another one started. These were all missing links (only now they had been found). It was a classic discovery, a glimpse of the larger patterns of life.

161 (80 Myr)
Sea urchin in flint
West Sussex, England

The Chalk is among the softer rock units in the world, easily eroded away, as the spectacular cliff falls along its outcrop demonstrate. But it contains one of the hardest rocks – flint – within its strata, in an association that is pretty much ever-present in this most distinctive of rock formations. The flint is the gift – or perhaps sacrifice – of one kind of fossil, which in disappearing often gave form and solidity to another. The substance of flint is silica, which was also the stuff that was used by some kinds of organism, such as glass sponges, to build their skeletons. The sponge-silica, though, is of the biologically produced opaline form, which dissolves away more easily than does the silica of typical quartz – or of flint, for that matter. So, the fossil sponges, once entombed in the chalky oozes below the Cretaceous sea floor, slowly dissolved away. The silica from them then precipitated into solid form once more, as concretions of flint. Sometimes this was around the sponge-shapes left in the rock (and so we know they existed). And, quite often, this took place within hollow spaces inside sea urchin skeletons, to marvellously replicate their shape, as the most durable of fossils.

162 (80 Myr)
Gryposaurus, hadrosaur
Alberta, Canada

In the dinosaurs' long Indian summer of late Cretaceous times, the duck-billed dinosaurs often featured in those landscapes. *Gryposaurus* was one such, and had evolved almost as if in anticipation of the plastic models and cartoon strips to come, by which humans now pay homage to the dinosaur world: not only did it have the duck-like bill of its kind, but its upper part was arched, Roman nose-style, to give it a most aristocratic appearance, perfect for that Hollywood starring role as the more friendly kind of dinosaur. But of what demeanour, exactly? Palaeontologists now puzzle over the exact use of that finely arched beak. Did it somehow help with the feeding process, grazing among lush Cretaceous vegetation? Could it give visual signals to other dinosaurs in the clan? Could it have been used by male gryposaurs in face-offs during the mating season? Or could it have been used as an echo chamber, to lift in dinosaur song? These are some possibilities to work into the plotline, just to add an extra dimension to the creative process.

163 (80 Myr)
Dinosaur coprolite
Utah, USA

Coprolites, the fossilised droppings of dinosaurs and other animals, are almost always cast as an excuse to add some low comedy in palaeontology. Sometimes that comedy could be deliciously subtle, as when that brilliant but impoverished and habitually patronised nineteenth century fossilist, Mary Anning, presented a coprolite ('some four centimetres high and perfectly proportioned') to her fellow savant, the Reverend William Buckland, Dean of Westminster. One wonders if she kept a straight face. But coprolites in the 19th century had a different resonance, too. Like the bones of dinosaurs and marine reptiles, they are stuffed full of one of the prime ingredients of life – phosphorus. Buckland was indeed one of the discoverers of this potential link between life ancient and modern and, as a result of his urging, 'coprolite workings' sprang up around particular fossil-rich beds to extract this life-giving stuff and process it, for farmers to spread on the fields to feed the rapidly growing population of Victorian England. That coprolite trade disappeared a century ago, as richer phosphorus sources were found elsewhere in the world. But when those are exhausted, we may, one day – and all joking apart – have to turn back to the dinosaurs, and the gifts of their mighty digestive systems.

164 (78 Myr)
Ammolite ammonite
Canada

Ammonites are beautiful fossils, but mostly the ammonites themselves are… gone. Not just the soft parts – eyes, tentacles, and such, as is usual with fossils – but also the spiral shells. These were made of a calcium carbonate mineral, aragonite, which has usually been completely dissolved away by subterranean percolating waters, as the fossil has lain underground for millions of years. So the 'ammonite' that one sees is usually simply an impression, or is seen as some kind of later mineral growth, as in a pyritised ammonite. But just sometimes, if the ammonite has been entombed in a particularly impermeable kind of clay, the aragonite of the shell can survive, even until today. There is an area of the Canadian Rockies where there are such ammonites, and these are extra-beautiful. The shell material is deeply lustrous like a pearl or abalone shell: indeed, the material it is made of (nacre) is essentially the same. They are so beautiful, indeed, that they have been classified as a new kind of gem, ammolite.

165 (75 Myr)
Gastropod
Gobi Desert, Mongolia

Where might a humble snail seek shelter in the dinosaur-haunted Cretaceous world of what is now the Gobi desert? The dinosaurs would be the least of its problems for, then as now, much of the Gobi was a desert. Indeed, the way that those bones are preserved in the desert sandstones (the dinosaurs likely perishing in sandstorms) without mineral overgrowths and appearing white, unlike the normal brown to black colours of fossil bone, may literally have given rise to legend. In the times of ancient Greece and Rome, travellers to the distant Gobi would have seen those bones, and thought them the remains of animals only recently dead (with perhaps their living relatives in the next canyon, waiting to pounce): and hence came the idea, into human heads, of mythical beings such as the griffon. This kind of place, now as in the Cretaceous, is not one where a snail can survive for long. So where? The Cretaceous desert strata of the Gobi are interlayered with other strata, that represent rivers and lakes, which advanced across the terrain when climate became wetter and shrank back when arid conditions returned. It is these kinds of strata that can host a fossil land snail, and from which this specimen was likely gathered. Follow the weather in the rocks, and it can lead you to the fossil – even at the most modest scale.

166 (75 Myr)
Sabalites longirhachis, palm wood
Europe

In the Cretaceous, a new palette of colours came to the land, as the flowering plants appeared and prospered – and carried on prospering, to become by far the most diverse group of plants alive today. Among these were the palms which, fittingly for such a greenhouse world, spread widely in those times. The palm, *Sabalites*, could appear in any film or cartoon about a desert island, with a starburst of leaves above a straight five-metre trunk, although its preferred milieu took the form of tropical wetlands. It kept impressive company, as the strata it is found in also contains fossil footprints of the sauropod dinosaur *Titanosaurus*. This would have been hungry as well as impressive company, of course, with a bulk in excess of ten tons to maintain, and so may well have used its long neck to graze on those *Sabalites* leaves, and the revolutionary flowers in their midst.

167 (75 Myr)
Chalk
Norfolk, UK

This layer is at the heart of the Cretaceous – for the very name is derived from the Latin 'creta' for chalk. The Chalk strata usually only form the upper part of the Cretaceous strata, but nevertheless the coincidence of rock and time is startling, and represents a very particular episode of planetary history. One can follow the brilliantly white Chalk layer, often approaching a kilometre thick, across much of the world. It is made up of countless tiny fossils called coccoliths (too small to see properly even with a normal microscope – one needs an electron microscope to examine them). It represents, moreover, the appearance of a new kind of life, in the form of lime-secreting oceangoing plankton. This biological revolution coincided with a time of greenhouse Earth, when polar ice melted and sea level rose to cover much of the continents with water – and with the chalk ooze, slowly building up from the endless rain of dead plankton. It was a world that we should now examine carefully, not least because we are now most energetically encouraging the return of those conditions.

168 (75 Myr)
Straight-shelled cephalopod
South Dakota, USA

Towards the end of the Cretaceous, the ammonites that, from straight-shelled ancestors, had evolved into so many variations upon the theme of a neat and tight spiral, began to repeat ancient patterns, and straighten out once more. *Baculites* is a fine example of this trend, with a straight or gently curved shell that may be a few centimetres long in some forms, and reach two metres in others. One wonders what it may have been like, beyond such questions as what did it eat and how fast could it swim. One of its relatives in those times, *Diplomoceras*, which was even more bizarre, being shaped like a giant paperclip, has been estimated to have lived for up to 200 years, based on the analysis of what appear to be annual chemical patterns in its shell. This gives pause for thought. Their relatives today, octopus, squid and cuttlefish, are known to possess considerable intelligence, but only live for a few years. What might their large, complex relatives of the Cretaceous have learnt and achieved, if they had such great longevity? Could we be interring, here, the mortal (and now finely powdered) remains of one of the philosopher-poets of the Cretaceous seas?

169 (70 Myr)
Plesiosaurus, long-necked marine reptile
Morocco

The plesiosaurs, those long-necked models for the monster that is sought – alas, forever unsuccessfully – in the deep and murky waters of Loch Ness, were one of the most successful predator-designs of Mesozoic times. Appearing more than two hundred million years ago in the latest Triassic, they made hay in the Jurassic, and held their own throughout the Cretaceous. This even went on into late Cretaceous times as formidably scary competition (and, for the plesiosaurs, likely predators too) appeared in the shape of the mosasaurs, and the ichthyosaurs and pliosaurs fell by the wayside, extinct well before the end-Cretaceous catastrophe. With such durability, one wonders why no plesiosaur-doppelganger is present today (the mythical denizen of Loch Ness excepted, of course), in the way that the dolphins have evolved to have much the same shape and position in the marine ecological web as the ichthyosaurs. There are plenty of fish and squid in the sea, still (the main plesiosaur diet), so perhaps something has fundamentally changed in the marine ecosystem to prevent a return of this body plan. This layer of the urn, thus, holds larger mysteries, to mirror the planet itself.

170 (70 Myr)
Mosasaurus, aquatic lizard
Morocco

In the late Cretaceous oceans, the mosasaurs were the tough new kids on the block, apex predators with an enormous skull and wickedly sharp teeth, that could grow to 17 metres in length. They created a stir then, likely contributing to the demise of the pliosaurs and ichthyosaurs, and are still making waves now. A fossil skull found in a Maastricht quarry in 1780 became the sensation of that city and a source of civic pride – until Napoleon's invading troops seized it in 1794 and carted it off to France (leaving, in some accounts, 600 bottles of wine to soften the blow). The skull of 'The Beast of Maastricht' was duly admired and scientifically described by the great Baron Cuvier, and since then has resided in the Paris Museum of Natural History. And, rather like Elgin Marbles, it has been a small persistent source of international tension from that time. Maastricht, politely but insistently, would like it back. Paris, with equal politesse and determination, is not letting go. The spirit of the mosasaur, that plundered the boundless Cretaceous seas, would be amused at this tiny example of human rapacity.

171 (70 Myr)
Silts from an ancient ocean floor in Antarctica containing fossil woods from lush forests
Seymour Island, East Coast of Antarctic Peninsula

Antarctica may seem like a place of endless ice and snow, an eternally deep-frozen continent. The 'eternal' is strictly relative, though. To human perceptions, 34 million years is quite long enough to be considered eternal, but on a geological scale it is simply the moderate interval of time that has passed since quite suddenly ('quite suddenly' being over about 200,000 years) Antarctica went from being a place something like New Zealand today, to something like, well, Antarctica. This layer is from an even warmer time some seventy million years ago, in the Cretaceous Period, when Antarctica was a place of lush forests, through which dinosaurs roamed. Today, we are very suddenly (even to human perceptions) loading the atmosphere with heat-trapping carbon dioxide, so that is approaching the levels seen in those ancient times when Antarctica was lush and warm. As the Earth adjusts to its new heat balance, this continent is beginning its move towards its ancient condition.

172 (70 Myr)
Crocodile skull bone
Lance Creek, Wyoming, USA

The crocodile family first appeared in Late Cretaceous times, and quickly developed the body plan that was to serve them well for the next seventy million years. These early crocodiles looked much like modern crocodiles – only some of them were very much larger. *Deinosuchus*, dubbed the 'terror crocodile', for example, reached 11 metres in length, getting on for twice that of today's crocodiles and alligators. With teeth the size of bananas, it could – and probably often did – make a meal of a dinosaur.

The crocodile family also had the precious gift of longevity, being able to weather the storm that was to come, whether through superb evolutionary design or just sheer good luck. So, we can admire their more modestly-sized members in the flesh – if still cautiously, of course – rather than having to bring fossil bones to life in our heads.

173 (70 Myr)
Hippurites, rudist bivalve
Southern Europe

When that great French naturalist of Enlightenment times, Jean-Baptiste Lamarck, found some strange cylindrical fossils in the early nineteenth century, he did not have a clue what they were, but such ignorance was (and remains) no barrier to biological classification. He called them rudists – from their rude appearance – and set about recognising and describing different varieties of them (many of which remain valid today). It is now known that the rudists were a bizarre form of bivalve mollusc, with one of the paired shells elongating into a tube that had one end anchored to the sea floor, while the other shell was reduced to being a lid on the top. The rudists, in fact, were adopting the lifestyle of the corals – and so successfully, indeed that rudist reefs formed and spread widely in Late Cretaceous times, outcompeting the retreating corals. The rudists were likely helped here in being able to better tolerate the high global temperatures of those times, on what was most emphatically a greenhouse world, while the corals, more sensitive to the rising sea temperatures, suffered (as they are beginning to do today). The rudist reefs must have been an extraordinary sight, as they extended across thousands of kilometres of those shallow sea floors, including lining both sides of the once-mighty Tethys Ocean. Like much else, though, they did not survive the catastrophe to come, and so they are one more part of the lost world of the Mesozoic Era.

174 (68 Myr)
Triceratops, head frill bone
Perkins County, South Dakota, USA

Triceratops is something of an icon, instantly recognisable, and now pretty much omnipresent in the dinosaur world as reconstructed by humans, as – for instance – a star saurian of the film Jurassic Park. Yet, it was very much a Cretaceous dinosaur, and indeed one of the last to evolve, in the very latest part of the Cretaceous. In the little time it had on Earth, it did pretty well, and the structure of that monstrous head clearly had something to do with this. But quite how did that head function? The classic reconstructions show the frill that covered the neck, a part of which is now consigned to this artwork, as defensive armour. But the frill seems to be a feature of adult *Triceratops*, and so would not have been of much defensive use to delicate *Triceratops* youth. A heat regulation device or sunscreen? Examined closely, that idea doesn't seem to hold up too well either. A current idea is that it reflects what we humans might call vanity: that is, as a device to signal oneself to the opposite sex, like a peacock's tail or a Pierre Cardin suit. It's nice to see the dinosaurs – all too easy to portray as reptilian monsters – have traits that we recognise in ourselves. Life, perhaps, was ever such.

175 (66 Myr)
Cretaceous–Paleogene extinction event: rare prehnite and apophyllite after laumontite
India

The Deccan Traps in India is an enormous pile of basalt lavas that were erupted, quickly and voluminously, at the end of Cretaceous time. Much has been eroded away over more than sixty million years, but even what is left covers half a million square kilometres, is up to 2 kilometres thick and represents something like a million cubic kilometres of magma erupted to the surface. When such hot and gas-rich lavas pile up, they literally stew in their own juices, and the primary volcanic minerals are altered to secondary minerals, one of which is laumontite, one of the zeolite mineral family (which in this case has altered even further into prehnite and apophyllite). The bigger question of the Deccan Traps is whether their eruption was responsible for the death of dinosaurs and much else in the catastrophic end-Cretaceous mass extinction event – just as, in earlier times, the eruption of the Siberian Trap volcanic rocks likely brought the Palaeozoic Era and its life to an end. The Deccan Traps have long been suspects here. But, the current answer seems to be 'probably not', as the timing seems to be not quite right – and because a yet more malevolent suspect has turned up, as we shall see in very soon. The Deccan Trap lavas, though, might well have roughed up Earth's ecosystems, before an alien invader arrived to give a sudden coup de grâce.

PALEOCENE
66-56 MYR

176 (66 Myr)
Nuclear winter's end: material from the K-Pg boundary site, spherules that were ejected from the crater and tsunami layers
Brazos River, Texas

The strata of what is now the Brazos River area of Texas was, in latest Cretaceous times, a tranquil sea floor perhaps a hundred metres deep, below the reach of storm waves, where marine life went about its peaceable way. Then, a sudden interruption to that humdrum sedimentation: the sea floor was vigorously scoured, and a layer of blocks and gravel and mud was dumped upon it, settling out as mighty waves passed backwards and forwards before subsiding. A giant tsunami had just passed through on its way to devastate the North American coastline. That tsunami in turn had been triggered – all the evidence now suggests – by the impact of a ten-kilometre-diameter meteorite hitting what is now Mexico, more than a thousand kilometres away. It was to leave a 200-kilometre-diameter crater and its effects: wildfires, the chill of a nuclear winter from dust in the atmosphere followed by global warming, ocean acidification… There were many horsemen in this apocalypse, and when their work was done, the Cretaceous ecosystem had collapsed, taking with it the late-arrived *Triceratops* and other dinosaurs, ammonites, mosasaurs and much else, in the fifth of Earth's major mass extinction events. That instantly pulverised meteorite left its calling card all round the world too, in the form of a worldwide sprinkling of iridium and rock-melt droplets (one can find them in the Brazos River deposits too), to close the case. From the ruins, a new chapter in Earth's history was to open.

177 (64 Myr)
Hercoglossa ulrichi, nautiloid
Alabama, USA

There's an old saying that it's the squeaky wheel that goes the longest. Well, here, we are just after one of the major biological catastrophes in Earth history, which terminated all the dinosaurs (at least, all the dinosaurs that are not birds, for birds are technically dinosaurs), and likewise killed off the ferocious mosasaurs and plesiosaurs in the seas and also the sophisticated, complex highly evolved ammonites. But, when the dust from the impacting meteorite has settled, just what can one see come trundling through the slowly clearing ocean waters? Why, it's none other than one of the ancient forms of the *Nautilus* kind, that in one form or another have been around, not much changed, since Devonian times some three hundred million years before, and that, somehow, are with us still. This species, *ulrichi*, has a different first name, *Hercoglassa*, because of the fussiness of taxonomists, though it was originally described as *Nautilus ulrichi* way back in 1897 (and has also spent some time under the moniker *Enclimatoceras ulrichi*). No matter, it's all much the same thing, and it shows that, when the going gets difficult, it can be the simple designs that may best weather the storm.

178 (64 Myr)
Echinocorys obliqua, sea urchin
Denmark

We are now a couple of million years into what is simultaneously a new epoch (the Paleocene), a new period (the Paleogene) and a whole new era (the Cenozoic), following the dramatic termination of their predecessors (respectively, the Late Cretaceous, Cretaceous and Mesozoic). The complexities of geological time! – but look at the rock itself here, and you would wonder at what the fuss is all about, for it's chalk, that looks much like the chalk rock of Cretaceous time. It's only when you look in microscopic detail, at the fossil remains of tiny plankton in this Danian chalk, that the scale of the revolution becomes clear: the complex, diverse Cretaceous microplankton have disappeared, to be replaced by the few simpler forms that were the survivors, living as 'disaster species' that thrived in the ecological chaos after that huge meteorite impact. Living happily amid the sea floor oozes formed by the new microplankton were new species of larger forms of life, such as the new kind of sea urchin we have here. It is captured here doing its best to make its way in a new era – and with some success, too.

179 (57 Myr)
Ginkgo adiantoides leaf, living fossil
North Dakota, USA

The ginkgo appears to be a spelling mistake. The tree is now only native to China, and its transliteration should be gingko, but a mistake made in a floral atlas printed in 1712 was repeated in subsequent western scientific descriptions, and the misprint is now firmly stuck. It's evolution of a kind. But the tree itself is another survivor of the end-Cretaceous crisis, and represents an ancient lineage going right back to early Permian times – and so it has survived not just one major mass extinction event, but three, as a most resilient living fossil. But it reacted rather less well to the times of abundance following the end-Cretaceous catastrophe, as it has generally been elbowed out of living space by the burgeoning flowering plants until, by three million years ago, it came to survive only in a small area of China. Now, as humans are busily spreading them around the world again in gardens and parks – but also simultaneously destroying habitats and causing global heating on a wider scale – the dice for the *Ginkgo* have once more been thrown. They are still, indeed, up in the air, and who knows how they will land.

180 (Paleocene, precise age unknown)
Petrified Cinnamon tree
Colorado, USA

When one talks of old spice, few will take this to geological extremes – but consider the cinnamon tree (or trees, for there is quite a large number of species of *Cinnamonium*). Fossils of cinnamon tree leaves, and of the fragrant bark, have been reported right back to Cretaceous times, so we might have here, in the Paleocene Epoch, one more survivor of the intervening mass extinction event. (Though the use of 'molecular clock' information suggests that *Cinnamonium* did not go back quite that far). Questions of identity apart, why did this tree evolve such a heavenly fragrance? Most likely, the active ingredient of cinnamon, the aromatic oil cinnamaldehyde, is not at all heavenly for some of the life-forms that can damage a growing cinnamon tree. It has been shown to repel mosquitoes and their larvae, for instance, and to disrupt the ability of microbes to form biofilms and to 'signal' to one another. So, in eating a cinnamon bun, we are really taking advantage of some ancient biological warfare.

EOCENE
56-34 MYR

181 (56 Myr)
Puddingstone from Paleocene–Eocene Thermal Maximum
Hertfordshire, UK

For a rock so young, it's terribly hard. Only 56 million years old, and yet a geologist has to pound it quite hard with a sledgehammer to break any lumps off. It's a hardness that's doubly remarkable as the strata above and below are generally soft enough to break apart with your hands – or dig into with a shovel. This is the Hertfordshire Puddingstone, which has near-fabled status in British geology. It's made of a mass of beautifully rounded beach pebbles tightly cemented together by silica. Even more puzzlingly, this cementation seems to have taken place near the ground surface, soon after the layer of pebbles was washed into place, and not at any great subterranean depths. So how could this happen? It is suggested that this rock represents a 'silcrete', a kind of soil that forms in very hot, wet climates, conditions in which silica can be released from mineral grains to form a tough natural cement. And the prime suspect for these hot, wet conditions is an ancient global warming event which took place at exactly that time, and which marks a break between the Paleocene and Eocene worlds. The

Paleocene-Eocene Thermal Maximum, it's called. It had more consequences than just forming a quirky kind of rock.

182 (52 Myr)
Eocoelopoma curvatum, fish head
Isle of Sheppey, England

Now that we are in the modern era (geologically that is: we are still early in Cenozoic times, that we still live in), life becomes ever more familiar. *Eocoelopoma* is a scombroid fish; that is, it belongs to the mackerel and tuna family. Its remains are one of the many fossils one can extract from the London Clay, the deposits of a shallow, muddy sea sited where that capital city is now. It was a very warm sea too, for although the 'hyperthermal' spike of global warming at the beginning of this epoch had abated, global temperatures remained warm, and even continued to slowly rise again in what was still emphatically a greenhouse world. So, the fossil fish (and crocodiles too) come together with hundreds of plant fossils of tropical trees, such as palms and mahogany, washed out to sea. That London Clay sea apart, Britain was beginning to take on something like its present shape – although with some dramatic touches, such as mighty volcanoes in the far north-west, collateral damage as the Atlantic Ocean continued to open. It was so near to us in geological time – but in important ways, therefore, still a different world.

183 (52 Myr)
Fossil ray teeth, London Clay
UK

Not uncommon in the London Clay, they hardly look like teeth at all: more like oblong buttons, smooth on one side and ribbed on another. But they are teeth, and moreover of those most weird and wonderful members shark-relatives, the rays. And like sharks, rays too have soft bones made of cartilage, so in almost all cases, these odd button-teeth are all you find of them in the fossil record (not quite all: a few spectacular impressions of the whole fish have turned up as fossils, each one a museum piece). They are predators – but their ferocity is different to that of sharks, being directed at shelly animals that live on the sea floor, that these teeth are used to crush. By the time they swam in the London Clay Sea, rays were already an old lineage, having been in existence for some hundred million years – albeit youngsters by comparison with sharks, who could claim three times that.

184 (51 Myr)
Presbyornis bird tracks
Utah, USA

The dinosaurs did, of course, survive the catastrophe that brought the Cretaceous – and indeed all of the Mesozoic – world to an end. They now take the form of the birds, which are part of the same branch of life on Earth. The likes of *Velociraptor* and even *Tyrannosaurus rex* were feathered, we now know, as one mark of their relationship to the crow and the sparrow, and there are other such clues in the anatomy of their skeletons. *Presbyornis* was one of the surviving dinosaurs, or birds, of the Eocene world. *Presbyornis* was perfectly bird-like, and it would take an ornithologist to see that it wasn't one of the 10,000 or so bird species living today. It was part of the duck family, with bill to match, though it was rather taller and more graceful than most ducks today, as though it had ambitions of becoming a flamingo: an elegant entrance for us, into the blossoming bird world of the Cenozoic Era.

185 (51 Myr)
Lacustrine varves: a fossil record of Eocene lake deposition
Green River Shale, USA

As the Rocky Mountains began to rise in western North America, a lake began to form, that was eventually to cover part of what is now the Green River region of Colorado, Utah and Wyoming. Changing its size and shape as the landscape changed around it, and as climate fluctuated, it nevertheless persisted for about 6 million years. That is a long span of time, even geologically, but the lake also captured time-instants on a much more human scale. In the summers, plankton blooms grew and died, and their remains then sank to the lake floor to form dark layers, while in the winters, fine mineral layers accumulated. The annual lake floor layers that resulted, that geologists call varves, thus provide a very fine-scale chronometer to the history of the Green River Lake. It's a most useful scale to have, for the Green River layers also include finely preserved fossil fish (and other fossils as well, from insects to the first bats), and the varves allow their evolution to be tracked in real time.

186 (51 Myr)
Petrified bamboo
Blue Forest, Wyoming, USA

Not all of the giants of the Earth belong amongst the dinosaurs of the Mesozoic Era. Some are of more recent origin. That most gigantic and impressively fast-growing of grasses, bamboo, for instance, evolved in our own era, the Cenozoic. The layer here holds one of the oldest known examples of bamboo… perhaps! The Blue Forest plant fossils of Wyoming are undeniably beautiful, for they have been petrified by eye-catching combinations of the minerals chalcedony and calcite. That fossilisation has in some places preserved fine details, down to cellular level, but elsewhere all that is left are hollow rotted stems, now filled with gaudy mineral. So are these bamboo fossils real, or are they some other kind of thin stem turned into bamboo imposters by this quirky fossilisation process? It's a classic kind of question in palaeontology.

187 (45 Myr)
Snail, echinoderm
India

Fossil-collecting in Eocene strata can be a most productive pastime, especially where molluscs are concerned (and echinoderms were doing well then too). Many forms of them lived on the Eocene sea floors, 50 million years ago or so. Whatever you find, it will be testament to a long revolution in the nature of seashells, as the molluscs rose to dominance, for here the snails (or gastropods, to speak a little more technically) and the bivalve molluscs will almost certainly dominate, as they still dominate among the seashells one can find on beaches today. Major players in previous eras, like the brachiopods or 'lamp-shells' (dominant in Palaeozoic times, and abundant still in the Mesozoic) will be less common, or more likely absent. As for the echinoderms, you will most often need to use a hand lens, to see fragments of the distinctively grooved sea urchin spines. It is the arrival of the modern world, as played out on the seashore.

188 (45 Myr)
Eohippus, the 'dawn horse'
North Sea, Germany

Owning a horse in Eocene times would be easy on stable fees. In fact, a kennel would probably do. *Eohippu*s, the 'dawn horse', was about the size of a fox, although already somewhat horse-shaped, if in cartoon fashion. It would save on blacksmith's fees too – or perhaps one would need to use the fine skills of a jeweller instead, as this horse had five toes, with each of the four that reached the ground having a delicate little proto-hoof at the end of it. Over the next 50 million years, there would go on to be a long and complicated horse family tree, with our current horses and zebras as a couple of the twigs at its end (and with rhinoceroses as distant cousins). This is all part of the wider story in which the mammals, no longer literally under the feet of the dinosaurs, could finally expand into a kaleidoscope of extraordinary forms, to fill the ecological niches vacated by the departed saurians. The Age of Mammals was by now decidedly here, and was to lead to yet more extravagant designs.

189 (44 Myr)
Baltic Amber, fossilised tree resin
Lithuania

Amber, in ancient Greek myth, was the tears of the sisters of the dead Phaëton, son of Helios the sun god, the sisters themselves having been turned into poplar trees. The story may be legend, but the link with trees and with the sunlight that sustains them was likely more than coincidence. Indeed, Pliny, in Roman times, made it clear that amber was hardened tree resin, although he surely had no inkling of just how many million years such resin can survive, to stay translucent enough to show the tiny victims of this sticky insect-trap. Amber is first known from the Carboniferous coal forests that grew more than 300 million years ago, but the most prolific ambers are younger, like the classic Baltic amber that can turn up on beaches in eastern England. It hasn't floated across – it's not quite light enough for that – but the tidal currents that sweep the North Sea floors can bring it to these shores quite effectively. The fine preservation of the trapped insects – and occasionally such things as feathers and frogs too – can be spectacular, though it's of the external surfaces only. The interiors of these victims of the amber have long decayed away, a final meal for the freight of microbes that they carried within them.

190 (40 Myr)
Giant *Nummulites lyelli*
Egypt

A protozoan is usually thought of as tiny, the kind of thing that one has to peer down microscopes to see. But some protozoans grow gigantic – even as single-celled organisms. The foraminifera are amoeba-like protozoans that live in the sea and grow elaborate calcium carbonate skeletons, that are usually pinhead-sized. But some grew bigger, and *Nummulites* was the behemoth of them all, growing disc-shaped skeletons with many internal chambers arranged in a spiral pattern. In Eocene times these reached the size of a tea-saucer and likely lived to be a hundred years old, to judge from the chemical patterns within them: a quite monstrous scale of both space and time for a single-celled organism. *Nummulites* skeletons piled up in masses on sea floors at times when reef-forming corals were in retreat, as the seas had become too hot for them. Those masses of skeletons then formed thick rock layers, as such things do. Much later, the nummulitic limestone rocks that resulted entered the most aristocratic of company, when the Egyptian pharaohs used them to build their pyramids.

191 (38 Myr)
Zygorhiza, whale
South Carolina, USA

Few kinds of organisms show the potential and sheer scale of change through biological evolution as well as do the whales. Early in Eocene times, the ancestor of the whales was a wolf-sized four-footed mammal that paddled by the shoreline, and perhaps tried to swim out a little to hunt. Fifteen million years later, from this unlikely origin – and in the absence of competition from the by-then-vanished mosasaurs and plesiosaurs – there had evolved the early whale *Basilosaurus* (given the saurian name of 'king lizard' because its bones were originally thought to be those of a reptile), up to 20 metres long with an odd, somewhat eel-shaped body and ferocious teeth, an apex predator that dined on fish and sharks. *Zygorhiza* is its little cousin, that reached just some 5 metres long. The whale family tree, of course, was to produce yet more extraordinary marine mammals, such as the baleen whales that include the largest animal that has ever lived, the blue whale. The possibilities of life, therefore, given ecological space and a little time, seem almost limitless.

192 (35 Myr)
Titanotherium ingens vertebrae, Brontotheres
South Dakota, USA

While the whales developed mightily in the oceans, the explosion of animals across the land was no less remarkable. We must recall that there were mammals throughout the entire Mesozoic Era, but their development had been firmly kept in check by the dinosaurs, which hogged all of the top spots in the ecological web and, while they were alive, didn't let go. The mammals, in those days, never got much bigger than a badger and, in the aftermath of the end-Cretaceous extinction, didn't include anything much bigger than a rat. That was the starting point. Then, absent the dinosaurs, there was space to expand, which they proceeded to do, in extraordinary fashion. Here, we have the truly titanic example of *Titanotherium*. This evocative name now, alas, is obsolete, for this animal now goes under the name of *Megacerops*. No matter: whatever name is applied, this animal is broadly rhinoceros-shaped (and is indeed a relative) but it was far bigger than any rhinoceros alive today, two and a half metres tall at the shoulders and up to five metres long. Like many of the truly huge animals, its diet was vegetarian.

OLIGOCENE
34-23 MYR

193 (33 Myr)
Dawn Redwood, *Metasequoia glyptostroboides*, living fossil
Oregon, USA

We have another living fossil here, captured almost exactly two-thirds through its remarkable lifespan, that started in Cretaceous time, some one hundred million years ago. *Metasequoia*, or the Dawn Redwood, over that time spread from North America to Asia, even reaching Japan, before the fossil record petered out in Ice Age times, a couple of million years ago. And that was thought to be it – until small living populations were found in small areas of central China. Amazingly, the living species cannot be told apart from most of the fossil specimens over that long timespan, so it's a fine example of evolutionary 'stasis' in the fossil record. After that near-brush with extinction, this handsome tree has been replanted in parks and gardens around the world, and generally seems to thrive in these new settings. So does that mean that its future is now set fair for another hundred million years? That's hard to say, but while we persist in arm-wrestling the climate into the kind of greenhouse state that *Metasequoia* experienced for most of its existence, then perhaps it is, at least, now better placed to survive in the new evolutionary stakes.

194 (30 Myr)
Oreodont femur
Nebraska, USA

The 'Grande Coupure' it's called, or the 'Great Break' – one in mammal populations that is, a kind of changing of the guard as some kinds of mammals became extinct while others evolved into a range of new forms. And yet, the cause lay far to the south as, over a couple of hundred thousand years, Antarctica transformed from a continent with extensive lush forests into a barren, ice-covered one. That transformation, almost exactly 34 million years ago, seemed to have been triggered by a drop in the amount of carbon dioxide in the atmosphere, and that in turn had consequences in the world oceans – the depths of which turned from tepid to bitterly cold, as icy brines poured in from the south – and in the Earth's climate, which turned generally cooler and drier. And that, in turn, within this complex meshwork of cause-and-effect, profoundly affected plant and animal populations, and changed the trajectory of their evolution. It was the beginning of a new 'icehouse' phase of Earth, that is still with us today, in a planetary transition that we now, with due formality, call the boundary between the Eocene and Oligocene epochs. The oreodonts, a kind of 'ruminant hog' that is no longer with us today, were then doing well in those changed times and conditions.

195 (30 Myr)
***Mesohippus*, three-toed horse**
South Dakota, USA

Some groups of animals came pretty well through the 'Grande Coupure' that caused something of a revolution among the world's mammals, as Antarctica's ice rapidly grew large at the dawn of Oligocene times, and spread a chill through the Earth's air. And in truth, the then-isolated continent of North America suffered the effects of the Grande Coupure less than did those of Europe and Asia. It was undergoing its own slow changes, notably as the Rockies began to rise, to give cooler and drier 'rain shadow' climates to the continent's centre: a kind of preparation, one might say, for the North American flora and fauna to the global cooling shock as Oligocene times began. So here, in this urn layer, we welcome *Mesohippus*, the next stage of horse evolution: a little taller than its predecessors, at two feet or so, now with just three toes: the central one being stronger, if not quite being a hoof yet. *Mesohippus* survived pretty well across that transformational boundary from Eocene to Oligocene times, as it grazed those emerging mid-continent plains. There was more to come from this line, but it could afford to take its time: this evolutionary race could, for now, move at a canter.

196 (30 Myr)
Saber-tooth Cat limb bone
South Dakota, USA

When a new kind of food comes on the menu, then sometimes it's useful to bring some new cutlery to the meal too, to take full advantage of the feast. As mammals continued to expand into the evolutionary niches left by the departed dinosaurs (the non-avian dinosaurs, we must keep reminding ourselves, for those dinosaurs we know as the birds are still alive and well), then one niche it took a little time to fill was that of the very large herbivore, of the kind of brontotheres, mammoths and such. It took a couple of tens of millions of years to evolve to this scale from the mammal starting point, which was about the size and shape of a rat – all that survived as the Cretaceous world collapsed. But once these monumental beasts evolved, then their very size alone could baffle a predator, and was a protection in itself. One response from the predators was evolving a means of getting inside all that solid flesh, and the saber teeth of that iconic and fearsome member of the cat family was one such. It was clearly a way to bite very deep, with dagger-like thrusts where strength of the neck muscles was likely more important than powerful jaws. An impressive strategy, but also a precarious one, as the saber-tooth mechanism evolved separately in several different animal groups, dying out each time as conditions and the food supply changed. It was one of the world's wonders, nevertheless.

197 (30 Myr)
***Poebrotherium*, primitive camel brain**
Utah, USA

When is a camel not a camel? When it lives in the Oligocene, one might hazard in response to that question. *Poebrotherium*, an animal of that time, was biologically a fully paid-up member of the Camelidae, but would confuse a child brought up on the traditional picture book version. A little less than a metre in height, it looked more like a delicately–boned llama – or even a gazelle – than a camel. Neither did it live in deserts, but rather inhabited the forests and grasslands of the North American continent. Its name means 'grass-eating beast', though it's uncertain whether grass or a more mixed herbivorous diet featured on its menu. One might say that it was part of the journey of that family along its long and many-branched family tree.

198 (30 Myr)
***Hyracodon nebraskensis*, sheep-sized running rhino**
South Dakota, USA

Look at a horse and a rhinoceros today, and you would be hard put to say that they are relatives. And yet they are, as detailed study of their anatomy shows – perhaps not very closely, but at least they belong within the same order of mammals. That similarity grows upon tracing these two kinds of animals back in time. In the Oligocene, the rhinoceros relative *Hyracodon* looked not unlike the early horse *Mesohippus* we met a few layers lower down: both were lightly built animals a metre or so tall, adapted to speedy running on the North American plains (and *Hyracodon* didn't have a horn at the end of its nose). So, not one of the giants of the past – though *Hyracodon* did at least have an impressively bulky relative in those days, in the 20-ton, five metre-tall (and also horn-less) *Paraceratherium*, one of the largest beasts ever to walk the Earth. Family connections, then as now, can certainly spring some surprises.

199 (30 Myr)
***Merycoidodon culbertsoni*, oreodont upper skull**
South Dakota, USA

We met the oreodonts a few layers back, in musing upon the key to their success: the great shake-up of mammals that came as ice grew on Antarctica and threw the Earth's climate out of its previous kilter, when what we now call Oligocene times began. But what of the animals themselves? It's quite a family, now usually called the Merycoidodontidae, with a dozen subfamilies, each containing a few genera, with the *Merycoidodon* now gracing this layer being just one genus among this bewildering (and tongue-twisting) menagerie. The merycoidodonts thrived in the cooler, drier climates that ensued. Their older, simpler name of oreodonts ('mountain teeth') gets across at least one aspect of the anatomy of these rather hog-like herbivores, although they were a little more closely related to camels than to pigs (while camels then, as we have just seen, included some rather gazelle-like creatures). It was a mammalian merry-go-round revolving vigorously enough to make your head spin, all part of this new kind of life.

200 (30 Myr)
***Palaeolagus*, lagomorph, extinct rabbit**
Wyoming, USA

Rabbits do not fossilise so easily, even though they are often abundant as living animals: their bones are small and light, and all too easily carried away and crunched up by their many predators and scavengers. But some scattered fossil bones of *Palaeolagus* in the Oligocene strata of North America suggests that it was both related to modern rabbits and also quite rabbit-like – a departure from of the mammalian shape-shifting that we have seen in adjacent layers of this artwork. The artistic reconstructions of *Palaeolagus* even give it long rabbit ears, though as ears – whether rabbit or human – are among the least fossiliseable parts of their anatomy, that might be as much artistic licence as scientific reconstruction. Nevertheless, unconsciously or not, it does emphasise that the world, by Oligocene times, was becoming more familiar, and also – a planetary quality not to be disparaged – a little more cute, too.

201 (28 Myr)
Whale ear bone
South Carolina, USA

How whales came to be what they are is one of the most extraordinary stories in all of biological evolution. That a blue whale – the largest animal to have ever lived (as far as we know) – could have its origin in a wolf-like animal paddling by the shore seems more akin to a 'Just So' story than to reality – yet it happened, and the fossil evidence proves beyond any reasonable doubt that it happened, and for good measure gives a good idea of quite how this transformation took place. The Oligocene was the time of the emergence of the particular kind of whale of which the blue whale is the apogee: those whales that don't have teeth, but rather have developed that remarkable biological development that is baleen: immense comb-like plates that allow the animal to filter enormous volumes of seawater to extract countless small plankton such as krill. This biological invention proved marvellously profitable, and baleen whales went on to grow larger than the toothed whales (though nevertheless remained their victims and prey, even up to the present day). Amid this endless arms race, it is a shame that we have little means of reconstructing another, gentler facet of ancient whale life. Did they sing to each other, as modern whales do? As song doesn't fossilise, we must, for now, leave to our imaginations quite what messages were received by this whale ear bone.

202 (28 Myr)
Mollusc
Australia

Now we are in the Oligocene, the planetary state that had become, in the broadest of senses, akin to the one we live in today. That is, there is a large mass of polar ice (for now, just on the South Pole) that takes water out of the ocean and stacks it up in frozen form on land, and in so doing lowers sea level and also, by various global teleconnections, cools the whole world. How do we track the behaviour of this new climate state, of what is often called an icehouse world? One way to do this is by seeing how climate affected the living organisms in those far-off days. Fossilised molluscs such as bivalves include clues to ancient climate, once we develop the wit to find them and read them. One such clue is the type of mollusc itself, for some like warm waters and others prefer to live in cool seas. More subtly, as mollusc shells grow, their chemistry – of carbon, calcium, magnesium and other elements – can capture some hint of how the seasons changed, or whether water from melted ice affected the environment in which they grew. Extracting this kind of evidence is a painstaking task, of patiently microdrilling the fossil shell, growth layer by growth layer, and then chemically analysing these microscopic samples; but, it can yield hidden stories of climate change. The humble mollusc can come into its own here, as witness to a changing world.

203 (28 Myr)
***Palmoxylon*, an extinct genus of palm wood**
Germany

There are times when a fossil can represent not just a certain animal or plant, but also the kind of image that belongs within childrens' cartoons and holiday brochures: that, in this case, of the palm-fringed desert island or tropical beach. And so it is with *Palmoxylon* here, an extinct kind of palm that, in the Oligocene, has been found as fossils together with fossilised corals and marine molluscs: a combination that indicates a classical tropical shoreline being preserved within strata. The internal anatomy of *Palmoxylon* wood, with tough rod-like tissues, both gave the stem its strength in life, and its longevity in the after-life, for it seemed to lend itself to be fossilised by silica. The resultant *Palmoxylon* petrified wood was, much later, sought by native North Americans to make stone spear-points, knives and scrapers – and, rather later, by modern humans, to make fancy jewellery.

204 (28.5 Myr)
Libyan desert glass
Libya

It's a kind of glass that turns up across several thousand square kilometres of the deserts of Libya: translucent, greenish and beautiful enough to have been used as jewellery to adorn the Egyptian pharaoh Tutankhamun. Its origins, though, go back much further than even these ancient times. Almost certainly, it represents rock that was instantly melted by meteorite impact, immediately afterwards re-freezing as a glass. Tiny radioactive minerals within it act as atomic clocks that show that the impact took place a little less than 29 million years ago, and so within Oligocene times. What kind of impact, though? Microscopic diamonds found in one (possible) fragment of this glass led some researchers to think that it was a comet that exploded in the air just above the ground. But, the precise form of another microscopic mineral, zircon, within this desert glass suggests that it must have been reshaped by the immense pressures that came from the impact of a rocky meteorite with the ground. It is tricky work, this, trying to disentangle the exact course of a prehistoric catastrophe.

205 (26 Myr)
Microfossils, ostracods, echinoid fragments, foraminifera, and mammal and reptile bones
Brooksville, Florida, USA

Caves are wonderful things to explore, not least because of the marvellous record they contain of ancient life. And so, caves today contain not just the bones of Stone Age people, but also the tools they made, and even the paintings by which our ancestors re-imagined their own world of the Ice Ages. Caves, though, have been forming in limestone terrain throughout the long history of the Earth, and these yet more ancient examples can also sometimes be found fossilised. The Oligocene cave deposits of Florida are one such example, developed within limestones formed during Eocene times that were already twenty million years old by the time that the Oligocene weather systems eroded underground caverns, and filled them with sediment that we can dig into today. This sediment can contain marvels: not just the standard range of shells, but also fossils such as – in the case of these caves – the bones of Oligocene bats. Such bones are normally too thin and delicate to be easily fossilised, but within this sheltered cave system many survived, to help show how mammals conquered the air, in evolving a wing as finely engineered as those of pterosaurs and birds, but quite different from both. It's a story that we can now read, thanks to the tendency for some kinds of rocks to dissolve in the rain.

206 (25 Myr)
Water lily
Montana, North America

Water lilies are lovely things, and so have attracted admiration from individuals – such as Monet, who painted them obsessively – and countries (in Sri Lanka, they are the national flower) alike. But there is more to them than their elegance, for their evolutionary roots go back very, very far in time. Indeed, it has been suggested that they might be the key to the 'abominable mystery' identified by Charles Darwin, which was why the flowering plants arose so quickly, amid the dinosaur-haunted times of the Mesozoic Era, and then underwent an extraordinary expansion to become the dominant kind of plant on Earth. The water lily, it seems, was among the very first of the flowering plants to evolve, and its characters – including a short but prolific life cycle – may serve as a guide to understanding the success of the flowering plants as a whole. That demurely beautiful exterior thus hides some powerful secrets, and has long done so. The Oligocene water lily that adorns this urn layer was already part of an ancient line when it lived and died.

MIOCENE
23-5.3 MYR

207 (12 Myr)
Extinct sirenian (sea cow), dugong ribs, probably of *Metaxytherium floridanum*
Peace River, Florida, USA

The sirenians, or sea cows are large, gentle herbivorous sea mammals, their name deriving from them being mistaken for mermaids by fanciful mariners. They go back some 50 million years, though now they are much reduced through humans, either by design, through hunting, or accident (speedboats are a particular hazard). This species we have here is of an extinct dugong, and the chemistry of its fossil bones suggests a restricted diet, mainly of seagrass. The modern sirenian inhabiting Florida is from the other branch of the family – it is a manatee. By comparison with the ancient Florida dugongs, and with the dugongs that live today in the Indian and Pacific oceans, its feeds on a wider variety of coastal and marine plants, and this may help its chances of survival, as seagrass meadows represent yet another ecosystem that is now in severe decline.

208 (23 Myr)
Agatized coral
Florida, USA

The corals that have existed right through the Mesozoic and Cenozoic eras were of a different kind than their ancient counterparts of Palaeozoic times. Specifically, the fossils of their remains were less likely to survive the ravages of time and geological process. These 'modern' corals (their technical term is scleractinian corals, or more simply hexacorals) formed (and, indeed, still form) their skeletons out of a mineral kind of calcium carbonate called aragonite. It's a mineral that is hard, and durable physically – but chemically it dissolves away easily underground, through the action of percolating waters over millions of years. All that is left is a hollow mould, with just the impression of the coral's surface on its outside; all the internal detail of the coral is lost forever. In the case of this Florida coral that lived in Miocene times, that hollowed interior was then infilled, as the percolating subterranean waters changed their chemistry, with silica in beautiful patterns. It's a quirk of fossilisation, and a very attractive one. Aesthetics aside, the use of this aragonite as skeleton-builder for modern corals now increases the threat to them from human pollution, as this mineral is vulnerable to being dissolved, in life, as the oceans acidify. For corals now, it has become a matter of life or death.

209 (22 Myr)
Ophidienovum, snake egg
Germany

The Miocene was a good time for snakes. These most distinctive of animals had already been around for a long time. They first evolved way back in the Cretaceous Period, when the dinosaurs still reigned. Snake origins are a bit of a mystery, not least because their fragile bones mean that they fossilised only rarely. They may, perhaps, have evolved from land-living lizards sometime in Cretaceous times, more than a hundred million years ago. Or, they might have evolved from the mosasaurs, those marine reptiles of the Cretaceous oceans – there are some clues in the snake skeleton suggesting this. If the latter, that would be one of the very rare examples of re-invasion of the land from the sea (it has been quite a procession in the other direction, as we have seen with ichthyosaurs, plesiosaurs, whales and the like). So snakes were already ancient by Miocene times, when they prospered, and a number of new forms, including the vipers, appeared. This may have been because drier conditions, and grasslands, spread more widely across the world's land areas then.

210 (20 Myr)
Coralliophilidae, coral invertebrate
Java Island, Indonesia

'Coralliophilidae' means 'coral-loving' and this is a family (a real biological family) of snails (or gastropods, to use the technical term) that live on coral reefs. 'Coral-loving' in this sense refers to a nutritional rather than emotional attachment, for these snails are specialised to feed on the soft flesh of the corals. They are just one part of the complex, diverse coral reef system that evolved and developed, over millions of years, around the framework provided by the corals themselves. Many of these snail shells are spectacular, large, robust and armed with spiky projections. This extravagance reflects a peculiarity of the chemistry of the material of the shells, calcium carbonate. Unlike most minerals this is less, rather than more, soluble in warm water, and so is readily taken out of the seawater by animals in warm seas to build their shells (this applies to the corals themselves too, explaining why coral reefs are mainly found in the tropics and subtropics of the world). The coral snails, as such specialised feeders, are dependent upon the corals – so when coral reefs are threatened (as today) they too become endangered.

211 (17 Myr)
Cabochon, Indonesian blue amber
Sumatra

The Miocene deposits of amber – fossilised tree resin – in Indonesia are said to be the world's largest. Several thousand tons are mined each year, and one individual lump measured some five square metres – the largest single piece of amber ever found. Why so? The Indonesian forests of the Miocene, then as now, included abundant tropical trees of the *Dipterocarp* family, which includes one locally called the 'resin tree'. But yet another potential cause has been suggested to explain this prolific occurrence, in that particles of volcanic ash have been found within the Indonesian ambers. These islands are part of the Pacific 'Ring of Fire', the track along which Pacific ocean floor is slowly, inexorably, being destroyed, accompanied by powerful earthquakes and paroxysmal volcanic eruptions. This is not some global catastrophe, but simply part and parcel of how plate tectonics works on Earth (a process which is, overall, far more life-giving than destructive). The Miocene Indonesian forests, it has been suggested, were affected by a phase of particularly energetic volcanic activity, and responded by secreting more resin, as a means of protection from the volcanic dust and toxins. It is part of the natural give-and-take of the Earth.

212 (16 Myr)
Protoyucca shadishii, Joshua tree
Badger Flat, Nevada, USA

If you wish for immortality, it can be best to live amid peril and high drama. *Protoyucca shadishii*, an ancestor of the modern yucca tree, lived amid some of the most dangerous and explosive volcanoes of the Cenozoic Era, which were themselves ancestral to the mighty volcanic caldera of Yellowstone, which threatens to re-awake one day. The fossilised stems of *Protoyucca* lie among the voluminous pyroclastic flow layers from the 16-million-year-old Badger Valley caldera of Nevada (itself thankfully now extinct), and are beautifully preserved by volcanic silica. The drama, though, seems to have been more than a local catastrophe. These Miocene Nevada volcanoes have been linked with giant outpourings of basalt lava which can now be found by the Columbia River, and as these in turn were erupted, the whole world warmed into what is now called the Mid-Miocene Climatic Optimum. This was a couple of million years when the world warmed, to temperatures a few degrees higher than before and perhaps 7 degrees centigrades higher than today. Was this enormous burst of volcanism, and the carbon dioxide it emitted, responsible? The evidence increasingly seems to point to that. And yet, there is a conundrum. This increase in carbon dioxide seems to have been quite modest (to levels we will probably reach later this century, as human business continues) to give such a large global temperature increase. Climate, thus, may be more sensitive to modest rises in greenhouse gases than we have suspected. The past, therefore, with its envoy *Protoyucca*, may yet come back to haunt us all.

213 (15 Myr)
Turritella agate, marine mollusc
Brazil

Turritella is a marine snail, or gastropod, that, with its high thin spire shape, is one of the most common and distinctive shells that one can find today – most of us will have picked them up from beaches as children. It has long been a successful design, and one can find examples of various species of *Turritella* through strata that span all the Cenozoic Era, and indeed go all the way back to Cretaceous times. It is part of the great worldwide expansion of the 'modern fauna' in which molluscs play a prime role. 'Turritella agate', though, is not a real agate (which forms within volcanic rocks), but is a mass of such shells that are naturally cemented together by silica to make an attractive rock.

214 (14.8 Myr)
Suevite, Ries meteorite crater impactite
Nördlingen Impact Crater Complex, Bayern, Germany

One fine day, fourteen million, eight hundred and eight thousand years ago (plus or minus thirty-eight thousand years, according to the latest analysis) a ball of rock from outer space, more than a kilometre across and travelling at more than forty thousand miles per hour, collided with what is now the German plain, releasing the energy of a million atom bombs. It created a crater which one can still see: it's more than 20 kilometres across, and the picturesque town of Nördlingen now sits in the middle of it. Looking out from the town one can see the ramparts of the crater walls in the distance. The impact created a marvellously distinctive rock called suevite (it is one kind of 'impactite' formed by such calamities), which one can find in quarries in the town. It is used as a building stone, which seems a little prosaic for such dramatically formed stuff. Suevite is an intricate mixture of bubbly, instantly-formed-then-frozen pieces of rock melt, other rocky fragments, and micro-diamonds generated by the impact. For all the local and regional mayhem, though, with nearby rivers choked by debris and forests felled by the blast, and flurries of melted rock droplets reaching as far as the Czech Republic, this was no Earth-changing catastrophe, and caused no global mass extinction. In the millennia that followed, a lake formed in the crater, and local life resumed: it was just one more event – albeit a noisy one – in the Earth's long catalogue.

215 (14 Myr)
Petrified bog oak
Nevada, North America

Bog oaks are one of the common features of our most recent geological history, where trees (not necessarily oak trees) lived on wet, boggy ground. After they died, their trunks fell into the swampy ground, where the acid, oxygen-poor waters prevent decay. These tree trunks can last thousands of years, and only begin to decay if they come to the ground surface again. One can sometimes see them in the English Fenland, by roadsides and hedges, where farmers have pulled them out of the thick, peaty soils of their fields. Now take this kind of situation (minus the farming), and put it back 14 million years among huge, active volcanoes in what is now Nevada. Here, silica-rich volcanic groundwaters suffused the swamp-encased tree-trunks (with the trees likely having been killed and felled by powerful eruptions), to petrify their woody tissues. This particular kind of fossil wood shows a fine palette of colours – green, blue, brown, white – so that it has been given the local mineral name 'larsonite' and is used to make jewellery.

216 (10 Myr)
Cervus, deer
Germany

Just to emphasise how close we are getting to the present day, deer roamed the Miocene forests that are placed in the same genus, *Cervus*, as exist today in the form of the red and Sika deer and the elk. Nevertheless. these Miocene forest scenes would – to the keen-eyed naturalist – have looked just a little strange. None of the antlers of the Miocene *Cervus* bore more than two prongs, and so these animals would – no matter how adult – all have looked a little adolescent by comparison with today's magnificently-antlered stags. It's a tiny example of evolution in action.

217 (10 Myr)
Thinobadistes segnis, giant ground sloth, ossified sternum
Florida, USA

While the Miocene deer of the previous layer would look familiar – *almost* familiar – to us, this creature, which first evolved in the late Miocene, is like something out of science fiction. This is *Thinobadistes*, which was one of the first of the giant ground sloths to inhabit North America. It was not the most gigantic of these – later were to come such behemoths as *Megatherium*, up to 5 metres tall and weighing 4 tons – but contrary to our usual ideas of sloth-dom, it was an energetic traveller. It, or its ancestors, made it from South America, where sloths originated, to North America by island-hopping, as a strong swimmer, even before the Panama isthmus formed as a land bridge to link these two continents. The giant sloths were in general adventurous travellers, and used to range all the way from Patagonia to Alaska. Alas, for all their bulk, these gentle herbivores were no match for bands of humans armed with spears. Ground sloths disappeared from the mainland about ten thousand years ago, as part of the great wave of megafaunal extinctions that followed humans across the world. They hung on a little longer on islands, such as Cuba, that humans took longer to find, living there to about five thousand years ago. Geologically, we have only just missed their company.

218 (8 Myr)
Clypeaster
Cessaniti, Calabria, Italy

The charming little town of Cessaniti in Calabria, on the toe of Italy, has a range of tourist attractions, including a 'sito paleontologico'. This probably refers to the local outcrops of sandstone, which illuminate the nature of the coastline in late Miocene time, about eight million years ago. The sea urchin *Clypeaster* is one of many fossils, from snails to sirens (not the seductive beings of legend that lure sailors to their doom, but a kind of aquatic salamander). *Clypeaster* itself, sometimes called a 'sea biscuit', still lives today, its flattened shape adapted to living in the shifting sands of a shallow sea floor. These fossils, though, are more than a local fossil paradise: they form part of the prelude to an event which literally rippled around the world. For just after these shallow sands were formed, the sea deepened in a sea level rise, that of the Tortonian Age of the Miocene, that has been detected in strata as far away as Patagonia. What caused it? Likely, the world warmed a little, enough to melt a little of Antarctica's ice, and to inundate the world's coastlines. It was just one of many oscillations of sea level: not the most dramatic one – but just enough to remind us that the Earth is a changeable place.

219 (6 Myr)
Copal amber
Kenya, East Africa

Copal can be said to be an amber that is not yet quite an amber. Not having yet hardened fully, it is still sticky and aromatic, and can be dissolved in an organic solvent, despite being millions of years old. The fossilisation of tree resin is clearly a long-drawn-out process! The molecular cross-links have not yet fully developed, in what is in effect a natural polymer – and so a natural analogue, in some respects, of modern plastics. Copal, therefore, is not so well suited for jewellery, but it is used to support a thriving trade as raw material for wood and picture varnish, and in some cultures it was used as incense. Nevertheless, copal, like amber, can trap and preserve within it the small organisms that lived in those forests – scorpions, beetles, wasps, ants and the like – that were unlucky or incautious enough to venture upon this sticky ground. They were fossilised, even if their tomb was still only in transit to its final solid form.

220 (6 Myr)
Megaselachus megalodon, shark
New Caledonia Island, Pacific

It's been quite the merry-go-round of names: *Carcharodon*, *Carcharocles*, *Procarcharodon*, *Megaloseuchus*, *Otodus*. These are all genus names that have been suggested to accompany a species name about which there is no such question of identity: *megalodon*, by most accounts the largest and most fearsome shark ever to swim the oceans. The tricky classification question around *megalodon* (for now, it seems to be *Otodus megalodon*) arises out of the way sharks fossilise, which is almost always as their many, almost indestructible teeth, while their bones, made of cartilage, rot away almost as quickly as their flesh after death. The teeth of *megalodon* are huge – wickedly serrated triangles that can be more than six inches long – and clearly show its status as super-predator. But, in the absence of more than occasional fossil scraps of the rest of the animal, the teeth bear the weight of the rest of the interpretation too, including its relationships to other sharks (hence those many genus names), and also its size. Thus, *megalodon* has been variously calculated to be anywhere between 13 and 25 metres long, all of this range being, in any case, firmly within the monstrous category.

221 (6 Myr)
Peccary pig tooth
Bone Valley Florida, USA

Fossil bones are usually rare, to be celebrated with each find. But in some strata, there are concentrations of them that are striking – and useful too, though sometimes in surprising ways. The fabled Bone Cabin of Wyoming is where a 19th century shepherd, seeking to build a shelter, used the only materials easily available on that hillside, which were Jurassic dinosaur bones (which included, when the site was properly studied later on, examples of the wonderfully named *Gargoyleosaurus*). Bone Valley in Florida is another such site, of rather younger geological age, where the strata include concentrations of bones, this time of Miocene mammals such horses, cats – and peccaries. There is a use to these bones too. They are made of calcium phosphate, and the Bone Valley strata are so phosphate-rich that they have been mined for fertiliser since the late 19th century. There is now, too, some urgency when we consider phosphate fertiliser, the use of which has grown hugely over the last century, for it literally helps us all stay alive. Nitrogen for fertiliser can be pulled out of the air, courtesy of the effective, if energy-intensive, Haber-Bosch process. But for phosphate, the main source is still its fossil stores, which are not so common, and the world may be approaching 'peak phosphate'. This layer of dust, hence, reminds us that we should respect our distant ancestors, and thank them for the lives that they still give us.

222 (ca 5.5 Myr)
Messinian salt deposits
Sorbas Basin, Spain

It was an extraordinary catastrophe. Not quite a global one, exactly, though in some respects it had a worldwide reach. But when, just under six million years ago, the Straits of Gibraltar were gently, tectonically, squeezed shut, in that dry climate it took only a thousand years or so for the Mediterranean Sea and its surroundings to dry up. It turned from a biological paradise into a hostile depression of baking salt flats, that reached up to five kilometres below the level of the adjacent, walled-off, Atlantic Ocean. The Messinian Salinity Crisis, it's called, and over the next 600,000 years influxes of sea water came in, each time to be quickly dried out. The resulting salt deposits are up to two *kilometres* thick beneath the Mediterranean Sea, and taking so much salt out of the world ocean would have reduced its salinity by some five percent. The gypsum deposits in this layer are from the edge of this hellscape, from a chemical forest of gypsum that grew in what is now the Sorbas region of Spain. Finally, the natural dam broke, 5.33 million years ago. In a flood of science fiction proportions, the Mediterranean Sea was refilled in, it is estimated, less than two years, and life began to thrive there once more.

PLIOCENE
5.3-2.6 MYR

223 (5 Myr)
Cetacean vertebrate
Yorktown Formation, USA

Whales have a curious evolutionary history, compared with, say, the mammals on land. Land mammals – once out of the shadow of the dinosaurs, and their tight grip they held for so long on the terrestrial ecosystem – evolved from rat-sized creatures to reach giant size in some ten to fifteen million years, early in the Cenozoic Era. But whales, for the best part of fifty million years, grew only modestly large, rarely exceeding 10 metres long – before then evolving into the great baleen whales, including the blue whale, the largest animal ever to have lived, only in the last few million years. Why this late appearance of gigantism? Was it a defensive response to the appearance of giant sharks such as *megalodon*, or because the food supply increased as plankton shoals grew larger? Perhaps the latter, it has been suggested, as the climate cooled towards the Ice Ages, and biological productivity increased in Antarctic waters. The Pliocene whale bone preserved here is part of the transition towards this marine world of giants, one which thrived before their industrialised slaughter by humans began. Perhaps, the giant whales will thrive again one day.

224 (5 Myr)
Dolphin ear bone
Belgium

It is appropriate to have the fossil ear bone of a dolphin included here, because it provides a clue to a facet of the lives of these endearing animals that helps explain their extraordinary success. Dolphins and other toothed whales are unique in the seas because they use echolocation to hunt and to navigate, as bats do on land. When did these animals develop the ability to echolocate? Sound itself does not fossilise – at least, not until humans invented long-playing records and CDs – but the organs that send and receive sound can sometimes be preserved as fossils. The fossilised inner ear of a dolphin – if closely examined by computerised tomography (CT) scans in an example of modern palaeo-technological magic – can show the detailed structure of the cochlea, with tell-tale signs that it acted as an echolocation receiver. Such fossils show that echolocation in toothed whales arose at least 25 million years ago, in the Oligocene Epoch – and so this technique had long been in use when this Pliocene dolphin created soundscapes of its underwater world, to help make its way through life.

225 (5 Myr)
Tomlinsonia stichkania, fossilised grass
California, USA

Grasses appeared late in Cretaceous times (their remains sometimes turn up in fossilised dinosaur poo), but they did not become widespread until the Cenozoic Era, when ecological niches such as savannahs spread widely, and many herbivores adapted to eating grass evolved. By the Pliocene Epoch, this was a much more grassy world. Grass is not the easiest stuff to fossilise, mind, other than its pollen and the tiny silica particles ('phytoliths') that form in its leaves. But this *Tomlinsonia* is beautifully conserved, the cellular structure of its stems preserved, as so often, by mineral-rich volcanic fluids.

226 (4.5 Myr)
Chesapecten jeffersonius, giant scallop
Virginia, USA

Chesapecten jeffersonius is a handsome fossil scallop that can be commonly found in the Pliocene marine strata of Virginia, and it is a fossil that has collected a number of honours: more, probably, than the average human. It is the first fossil to be illustrated from North America (in 1687) and, when it was scientifically described in 1824, it was named after Thomas Jefferson, a scientist (and much else) as well as President of the USA – and, likely because of these august connections, became the state fossil of Virginia. *Chesapecten* has, though – putting paleo-vanity aside – deeper stories to tell. It lived in a shallow sea that, in Pliocene times, covered what is now Virginia's coastal plain. This inundation was not so much due to movement of the Earth's crust, as because sea level in Pliocene times reached some 20 metres higher than today, as the world was a little warmer then than now, and much of the ice that now covers Greenland and West Antarctica was melted. This is now immediately significant to us, as atmospheric carbon dioxide levels in the Pliocene were naturally close to where humans, by burning fossil fuels, have pushed them now, at some 400 parts per million. So, we are now breathing Pliocene air – and waiting for climate and sea level to catch up.

227 (4 Myr)
Asteroidea, sea star
Middle East

Names can be tricky things. Sea stars are more commonly known as starfish (although they are not fish at all, any more than shellfish are fish). They are also known as asteroids (because they belong to the family Asteroidea), although that is yet more confusing because large lumps of rock in outer space are called the same thing. Names apart, these complex and fascinating animals have a long geological history, stretching back to the Ordovician Period, nearly half a billion years ago. Their fossil record, though, through that time span is not terribly good, as their multi-part skeleton tends to fall apart after death. This can make specific palaeontological questions challenging. For instance, the notorious and predatory crown-of-thorns starfish has, in recent decades, devastated many coral colonies, especially on the Great Barrier Reef. Is this a new phenomenon, caused or amplified by human disturbance? Or have such attacks taken place for thousands, or even millions of years? Genetic studies show that this voracious starfish, once thought to be one species, in fact consists of four very closely similar species, which may have separated as long ago as the Pliocene. Did the starfish mass attacks occur so long ago? Seeking fossil evidence would help resolve this question.

228 (4 Myr)
Coral
Indonesia

How did corals fare in the Pliocene? The question is a significant one, because, having created a Pliocene-like atmosphere, containing something more than 400 parts per million of carbon dioxide, we are now moving towards a warmer, Pliocene-like climate state, two to three degrees warmer than the Earth was before we started burning huge amounts of coal, oil, and gas. Reaching that state will likely take decades to centuries, just as a house takes a while to warm up when the thermostat switches on. And corals, we know, are already suffering in the extra heat from global warming. So, what might happen in the long term? A study of Pliocene corals showed that some corals fared better in those warm conditions, and some did worse. Those that fared best were small corals that live freely on the sea floor, which became more common. But the big coral colonies that form the framework of coral reefs did less well, and that matters because these are key to the enormous biological diversity of the reef system. Going back to the past, in this case, seems not such a good idea.

229 (3.5 Myr)
Meandropora tubipora, bryozoan
Suffolk, England

In the Pliocene, much of the area that we now call the county of Suffolk was underwater, when the sea was a little warmer and some 20 metres higher than today. We can still walk on the remains of that shallow sea floor – now that it is conveniently on dry land – and even reconstruct what that ancient sea floor was like. This has been something of a classic geological locality since the early 19th century, when the scholars studying it (who for a time included Charles Darwin) found many fossil examples of what they called 'corallines' within the sandy layers of that sea floor. The fossils turned out to be mostly not corals but bryozoans or 'moss animals', small colonies that are most familiar to us when they encrust seaweed. But the name of 'Coralline Crag' ('crag' is the local term for a shelly sand) has stuck since those days. The spectacular sand layering, we now know, is the result of tidal currents sweeping sand into large, mobile dunes and sand ridges – just as they do today in the tide-swept waters of the adjacent North Sea. It is a little eerie to go three and a half million years back into the past, to find the seashore of today.

230 (3.4 Myr)
Umbellularia, laurel
La Paz, Arizona, USA

Fossil wood in the Pliocene river sands of California and Arizona can be beautifully preserved. Tree rings can be seen, and the cellular structure of the wood, and even marks showing infestation by the larvae of bark beetles. This fossil wood can be used, too, to say what that part of the world was like then, in Pliocene times: a little more temperate and wetter than today, it seems, especially in winter. An indication of global climate change? Not altogether, for in working out what the climate of the past was like, local conditions must be considered as well as global ones. The mountains in this region had not, then, in the Pliocene, risen as high as they have today, and so it was easier for fog and clouds to come in from the sea.

231 (3 Myr)
Trichopeltarion, crab
North Canterbury, New Zealand

How much can a crab change in three million years? That was the question prompted by the discovery of a nice assemblage of fossil crabs found in late Pliocene strata at Motunau Beach, in New Zealand. Fossil crabs are not so very common, and these specimens were preserved by having calcium carbonate crystallising around them soon after their carcasses were entombed within the sediment of that Pliocene sea floor. The hard cannonball-like concretions that resulted can now be split open by the geologist, to reveal the fossil crabs within. These were of a species then new to science, *Trichopeltarium greggi*, and it was compared with the most closely related crab species that now lives in New Zealand waters, the wonderfully named *Trichopeltarium fantasticum*. How different is *greggi* from *fantasticum*? Not very much, at least as far as one can deduce from the preserved parts of the carapace: a slightly different outline, not as many spiny projections, a different pattern of bumps on the carapace. One needs to look closely to tell the difference. If the animal is well-fitted for its environment, it can stay the same, or very, very similar, for many, *many* generations. While we sensation-hungry humans focus on the dramatic events in Earth's history, long periods of stability are more usually the rule: something to reflect on in today's unstable and rapidly changing times.

232 (5.3-2.6 Myr)
Polonices, gastropod
Sahara, North Africa

Polonices is a sea snail, of the 'moon snail' type, that looks innocent but is a remorseless predator – usually of other snails, or of bivalve molluscs. Its murder weapon is a radula, akin to a tongue studded with tiny teeth, with which it drills through the shells of its prey, before dining on the soft parts within. How come one finds Pliocene fossils of this mighty hunter of the seas in the Sahara Desert? Most likely this is because of the relative warmth of Pliocene times, and the melting of part of the polar icecaps, allowing sea level to rise to cover part of North Africa. This marine inundation was probably short-lived, because the climate was soon to cool, ice was to grow again, and the seas were to retreat from the land. The Ice Ages were about to set in.

PLEISTOCENE
2,580,000-11,700 YR

233 (1,700,000 yr)
Acheulean war axe, Lower Paleolithic tool
North Africa

Humans from a species other than ours began to shape rock, skilfully and thoughtfully, to produce tools. The distinctive hand axes of the Acheulean culture – neatly pear-shaped to fit in a hand, and with a long cutting edge – date back to more than 1.7 million years, long before *Homo sapiens* appeared on the planet. This particular craft of axe-making was first practised by *Homo erectus*, or perhaps by an even earlier species, *Homo ergaster*, in Africa. Were these really war axes? Perhaps they could sometimes be used in fighting, or ritual display, when rival groups encountered each other. But their use was largely more prosaic: cutting meat (often secured by scavenging, rather than hunting); cutting and scraping animal hides; digging for roots. They could well have had a wide social purpose, as a skilful axe-maker may have been able to more easily attract a mate, and perhaps, it has been suggested, they formed the first kind of currency too. This new kind of tool did not then, however, spark a succession of further technological breakthroughs. Rather, this skill was passed from generation to generation for hundreds of thousands of years, later to be taken up by other species such as the Neanderthals. As an example of technology for slow and sustainable living, it can hardly be bettered.

234 (Pleistocene, precise age unknown)
Alligator *mississippiensis*
Florida, USA

The American alligator looks like an ancient monster from the dawn of time – and so it pretty well is. At least, the modern alligator is (as far as one can tell from shape of the skeleton) pretty much the same as the fossil alligator, here, from the early Pleistocene Epoch of Florida. Indeed, it is so close to fossil alligators of yet older times, reaching ten million years and more of the Miocene Epoch, that palaeontologists still argue over whether they are the same species or two very similar species. All of which adds up to saying that the alligator is highly adapted to its environment of rivers, lakes and swamps, and there has been little pressure on it to change, even through the many, repeated changes to climate and sea level over this long time interval. Over this time, it has been a 'keystone' species, in doing much to shape – as a top predator – wetland environments such as the Florida Everglades where it lives. Will its future be as long and successful as its history? Things have now changed in its home, where its place as top predator has been usurped by humans and probably also by Burmese pythons, introduced accidentally (or perhaps more precisely, frivolously) into the Everglades less than half a century ago, and now taking a firm grip on that landscape. Our ancient monster has a deadly new challenge.

235 (1,700,000 yr)
Fulgurite
Israel

Humans have always lived with fire. Well before they began to control fire (which our ancestors probably learnt about a million years ago or so), they would have experienced wildfires, and learnt to flee the conflagration – but, likely, also to use it, to hunt panicked animals as these fled the flames too. Natural wildfires are often caused by lightning, and lightning strikes can produce a very distinct type of rock structure, especially when they strike the dry ground of a desert or semidesert. The lightning bolt penetrates a little way into the ground, and melts the mineral grains, producing, after this cools, a rigid cylinder of fused sediment, which geologists call a fulgurite. One can find them in desert regions today, and also in ancient desert sandstones. They are reminders of the power of storms, and of fire.

236 (793,000 yr)
Tektites from a meteorite impact
Thailand

Large meteorite impacts are now very rare on Earth – luckily, for they can be devastating. It's not like in the old days of the first billion years of this planet's history, as much rocky debris in the Solar System was cleared away, mainly by crashing into the planets (one can see the scars of this early bombardment on the Moon, although on Earth these ancient craters have almost all been eroded away or buried). But such impacts still occasionally occur. The last major one was 793,000 years ago, when flying droplets of melted then quickly-quenched rock generated by the impact spread (as 'tektites') over an area from Indochina to Australia – about a fifth of the Earth's surface. Where did the meteorite land? This has long been a mystery, but clues now point to the Bolaven Plateau in Laos, where it seems that a crater some 15 kilometres across was formed by the impact, though later was completely buried under lavas from subsequent volcanic eruptions. Nearby debris layers, however, include mineral grains with microscopic 'shock' patterns that betray a cataclysmic nearby impact. What about the wider effects of this impact? Early humans of *Homo erectus* kind were living in China at this time, and their artefacts are found associated with the tektite layer: the felling of forests by the impact may have cleared ground to make it easier for them to make tools with.

237 (700,000 yr)
Gajah Purba, ancient elephant
Java, Indonesia

This elephant may well be a mastodon – but there are mastodons and mastodons. The extinct *Sinomastodon* from China and Java was not closely related to the more famous mastodon of North America (which, to add further confusion, is placed within the genus *Mammut*). And, in case your head is not spinning quite enough, although *Sinomastodon* looked very like an elephant it was not, technically, an elephant but a gomphothere, which was another kind of large elephant-like mammal which had had tusks and, probably, a trunk too. The tree of life can have many branches! And the animals that make up these branches could be widely dispersed, not least during the Pleistocene Epoch, as this was the time of the great Ice Ages. As ice began to repeatedly grow in the high northern hemisphere as well as on Antarctica, it drew water out of the oceans, making sea level fall. And as the sea retreated and the sea floor became dry land, it became easier for land animals – and later humans – to migrate between the Asian mainland and Indonesia. Yet later, one of those humans made a carving out of a fossil *Sinomastodon* bone. And now it is in this artwork.

238 (500,000 yr)
Acheulean jasper hand ax biface

This is a handsome as well as a functional artefact. Jasper is a form of silica that has a strikingly blood-red colour (it can have other colours too – yellow, brown, or even blue), with the red colour coming from tiny particles of iron oxide. Was it specially chosen, therefore, for its beauty, to impress fellow members of the tribe, or for some ceremonial use? It is hard to search so far back for motives, not least because it was another species of human making this axe, and not our own. Whatever its wider purpose or significance, this axe was made with technology that by now was more than a million years old, and so had been passed down for 50,000 generations or more (including across species barriers). Innovation, it reminds us, is a modern concept and – as we are finding out, with some disquiet – a double-edged weapon too.

239 (300,000 yr)
Bovidae, *Bos primigenius*, bull thigh bone
Germany

Bos primigenius, otherwise known as the auroch, has left something of itself for us contemporary humans, in being the ancestor of all of our domesticated cattle today. Little, though, of the fire and spirit of the ancient beast has survived in today's placid providers of meat and milk. The aurochs themselves survived for long enough for written records of their nature to be passed down to us, the last of its race dying in a forest in Poland in 1627. Julius Caesar said of them that they were the size of an elephant (only a slight exaggeration, as a bull auroch grew to be 2 metres tall at the shoulder) and that they spared neither man nor beast that they caught sight of. These fierce, almost untameable beasts had adapted to challenges of their own, in evolving amid the windswept grasslands that developed when the cold climate of the Ice Ages made the land too cold and inhospitable for forests to grow. The challenge of humans, though, proved too great.

240 (200,000 yr)
Bat and rodent bones on cave wall
Maryland, USA

Caves have been shelters and protective havens for man and beast long into the past, with words such as 'caveman' and 'cave bear' making that connection almost subliminal. But they can be traps, too, as in the Cumberland Bone Cave of Maryland. This was a thirty-metre-deep sinkhole with sheer, vertical sides dissolved by millions of years of percolating water in the local limestone rocks. Over perhaps a million years of the Ice Ages, it became a tomb for unwary animals that fell into its depths. These would try to survive for as long as they could on the bodies of previous victims, and so the myriad remains have been pulled apart and scattered, an endless jigsaw puzzle from which today's palaeontologists try to assemble whole skeletons of bears, peccaries, and wild cats. Mixed in too are the remains of invertebrates – beetles, snails, and millipedes – that lived around the cave. The bones in this layer of dust – of rats and bats – are of the few creatures able to get both into and out of the cave; for them it was a shelter.

241 (200,000 yr)
Cervus canadensis, elk jaw
Cass Country, Nebraska, USA

The elk (or wapiti) is now a thoroughly North American species as native, although in the later part of the Pleistocene Ice Ages it ranged more widely into Asia and Europe – being present in Moldova at the height of the last Ice Age, some 20,000 years ago, for example. The elk, today, are among the great migratory animals, following the retreat of the snows in the spring, and its return in the autumn. On the scale of the Pleistocene, too, they undertook larger migrations to follow the many twists and turns of climate. In effect, they were following an astronomical cue, for the pacemaker of the repeating cold glacial and warm interglacial conditions was set by the patterns of regular change in the Earth's spin around its axis and orbit around the Sun, which in turn control the patterns of the Sun's heat that we receive. The elk are just one of many species to have danced to this tune, in the regular rhythm of the Ice Ages. It's a tune now interrupted by humans, through our massive outburst of greenhouse gases, and we are not quite sure when it will return.

242 (130,000 yr)
Caribou tooth
Fairbanks, Alaska, USA

This caribou grazed on Alaska the last time global climate was as warm as it is today, one hundred and thirty thousand years ago, in what is known as the Last Interglacial, a phase of the Ice Ages which lasted some ten thousand years – roughly as long as our present warm phase has lasted. Indeed, the Last Interglacial may even have been fractionally warmer than today, and sea level rose to peak at 6 metres or so higher than today's sea level. These were balmy times for these caribou herds. A few thousand years later, glacial conditions returned and – with ups and downs – were to persist for a hundred thousand years. At their height, 20,000 years ago, a great icesheet covered North America, reaching south as far as Manhattan. But curiously, it did not cover central Alaska. As sea level fell by more than a hundred metres, Siberia joined with Alaska, and the region grew drier as the sea grew more distant. Whatever moisture arrived was caught by the Alaskan Mountains in the south. Inland Alaska became a frozen arid desert – no place, though, for a sensible caribou.

243 (50,000 yr)
Vombatus ursinus, wombat dentary
Australia

The wombat was one of the kinds of animals encountered, and hunted for food, by humans when they first reached Australia, some fifty thousand years ago. It survived this new kind of pressure and is still commonly present along the eastern edge of the continent, though its numbers and its range have shrunk. Some of its relatives didn't make it, though, and succumbed to hunting (and perhaps in part to climate change too) a few thousand years later. There was the giant wombat *Phascolonus gigas*, for instance, twice as long as the common wombat and weighing up to a quarter of a ton, which became extinct at that time, as did another 'giant wombat' (not a wombat this time, but related) *Diprotodon*, which was the size of a hippopotamus. When a 26-year-old Charles Darwin visited Australia in 1836, while voyaging on the *Beagle*, he was astounded at the animals he saw, quite unlike any he had seen before. These were just the survivors: had the full Pleistocene menagerie still been living, his amazement would have known no bounds…

244 (65,000 yr)
Neanderthal Mousterian hand wedge biface
Saint-Julien, France

We particular humans are now a lonely lot. Not so long ago, we shared the planet with other kinds of human – the shadowy Denisovans, the diminutive *Homo floresiensis* (termed the 'hobbit' in the gaudier press articles), the Neanderthals, and likely others. And now only we, *Homo sapiens*, are left, albeit in very great numbers. The Neanderthals lived for more than a third of a million years, before finally disappearing some 40,000 years ago. When their bones were first discovered in the mid-nineteenth century, they became the model for the popular image of the cavemen: stupid, brutish, and violent. It was an image that was long to persist. But now we know that their stocky build was an adaptation to the cold climates of the Ice Ages. The Neanderthals could make tools like the hand-axe that now lies in *Requiem*, use fire, weave textiles and rope, store and cook food, use medicinal plants, heal injuries, and – perhaps – make music, collect crystals and fossils, and paint scenes from the world around them. These relics are testimony to another kind of human perspective on the world.

245 (45,000 yr)
Mammuthus primigenius, woolly mammoth rib
Netherlands

There is no animal that symbolises the Ice Ages of the Pleistocene quite as much as the mammoth. This monstrous animal has left its bones and tusks for us to wonder at, and to puzzle over, and to spark many ideas. In the late eighteenth century, that influential savant, the Comte de Buffon, interpreted its bones, then being found far north in Siberia, as those of a large, warmth-loving African elephant (the skeletons are very similar), to suggest that the Earth had cooled since the days in which it lived. A generation later, Baron Cuvier, a celebrated anatomist, demonstrated that the mammoth was *different* from the living elephant – and that it was of a species no longer alive: a major step in demonstrating the reality of extinction in Earth history. And when frozen woolly mammoths were found in the Siberian tundra, they showed that these animals were adapted to bitterly cold, not tropical, conditions. The woolly mammoth, *Mammuthus primigenius*, is the last of the mammoth species. Long thought to have died out some 10,000 years ago, at the end of the last Ice Age, it is now known to have survived, in diminutive form, on Wrangel Island north of Siberia, until only four thousand years ago. Mammoths were therefore still living as the Egyptian pyramids were being built, as something of a final handover in the change from one kind of world to another.

246 (40,000 yr)
Cave bear
Romania

The many huge skulls and bones that were found in caves in olden times used to be thought to be those of dragons and were the wellspring of legends and myths. They were not the skeletons of those mythical fire-breathing animals, though, but of a creature almost as impressive. The cave bear of the Ice Ages could weigh up to a ton, larger than any bear alive today, though it was no fearsome predator, but sustained its huge bulk on a largely vegetarian diet. It became extinct some 25,000 years ago, as the last Ice Age was approaching its height. Why? Simple hunting by humans was not thought to be enough to drive this mighty beast to extinction, for an adult cave bear could defend itself against even a cave lion. Perhaps, it has been suggested, it was something more prosaic. Cave bears did indeed use caves, for both living in and for hibernation. A Neanderthal population, and then a growing one of *Homo sapiens*, also sought cave space for shelter. They may simply have crowded out the cave bear, especially as it sought to hibernate. This sounds plausible – though also a little melancholy, if it really was a housing shortage that brought about the demise of this magnificent beast.

247 (40,000 yr)
Aboriginal red ochre pigment
Australia

If one wants to choose a pigment that will last the ages, then red ochre is a very good choice. It is basically one kind of iron oxide, haematite, a mineral of a deep blood-red colour that persists even when it is finely powdered. Brown ochre is pretty good too – this is usually the iron hydroxide goethite (which is indeed named after the poet Goethe, who was a capable mineralogist in his youth). With oxygen in the local environment, these vivid minerals, with their iron safely in the oxidised, ferric, state, are almost completely insoluble, and so the art of the indigenous Australian people (and of the cave artists of Lascaux, Altamira and elsewhere) can persist for many thousands of years, to carry its message to us all today. But these mineral pigments have an Achilles heel. Submerge them in water that is stagnant, oxygen-starved, or bury them underground beyond the reach of oxygen, and this iron will eventually convert into its reduced, ferrous, state, where it easily dissolves (in some of the more famous and well-visited caves, the breath of many tourists, and subsequent mould growth, has started this process). The ochre, and the stories it conveyed, will disperse, and be swept away by the waters. It is art for the ages, perhaps, but geological ages and geological changes are more formidable barriers to memory.

248 (35,000 yr)
Bison priscus, bison bone
Siberia

The steppe bison lived for the best part of two million years of the Ice Ages, ranging across from Europe, Asia and north America and, like so many other of the great beasts of the Pleistocene, lasted *almost* until the present day, the last-known of its kind dying out a little more than 5000 years ago, in Alaska. We now know it mainly from its bones, but its likeness has been luminously outlined in red ochre in Spain's Altamira cave, made by people who seem to have hunted and revered it in equal measure. Alaska, too, has yielded a mummified steppe bison, killed by a lion and frozen hard before the meal could be finished, before being swallowed up by the permafrost. Found by a gold miner, its blue, mineral-coated skin gave it the name 'Blue Babe', and it now has pride of place in Fairbanks Museum. As a final touch to celebrate putting it on display, dining on this bison continued, after a gap of 36,000 years. A small piece of the mummified meat was chopped and made into stew for the scientific team. It was described as tough, with a Pleistocene aroma. The ghost of Blue Babe did not take its traditional revenge, though. All the diners survived the feast.

249 (30,000 yr)
Equidae, *Equus ferus przewalskii*, wild horse thigh bone
Germany

Przewalski's horse is a fine example of the difficulties of biological taxonomy. Even though still alive (if only just, and recently re-introduced back to the wild in its native Mongolia), this short, stocky animal has been variously regarded as a separate species from the common domesticated horse, a subspecies, or just a wild variety. How far did the range of Przewalski's horse extend during the Ice Ages? Cave paintings show horses that look like this in Europe, but the DNA extracted from associated horse bones suggests that these are ordinary horses, and not Przewalski's. So, in keeping with the best tradition of scientific caution, we shall consider the bone in the urn as possibly Przewalski's, and possibly not. But definitely horse.

250 (21,000 yr)
Halichoerus grypus, grey seal

How do animals cope when their world disappears? This was a question asked of the grey seal, and how it would have fared at the height of the last Ice Age, 21,000 years ago. It's a question that can be made specific, for the grey seal is a creature of the shallow seas of the continental shelf, diving down some tens of metres towards the sea floor, to dine on fish, crustaceans and such. But at the height of this Ice Age, the world's icecaps grew so large that they locked up enough water in frozen form for sea level to fall by some 130 metres, converting much of these shelf seas into dry land. Worse for the seals, they were pushed out of most of the few shelf seas that were left as the sea ice grew out much thicker and farther. The grey seal's feeding habitat contracted so much that their populations are thought to have fallen to perhaps only 3% of its former numbers, before bouncing back as the ice melted and sea levels rose again. It's an impressive resilience, that this species will doubtless need again.

251 (20,000 yr)
Silicified glacial coral
Poland

This coral did not live in Poland during the Ice Ages. Rather, it is a traveller in both space and time. It lived 400 million years ago or more, in a shallow sea, probably in what is now southern Scandinavia. In classic fossil coral fashion, the animal died and its skeleton was buried in the strata that built up on that ancient sea floor. Its skeleton was finely and durably preserved, the original calcium carbonate structure being replaced by silica, courtesy of the chemistry of the fluids that suffused those strata; this was to be important, for this tough silica would literally harden it for the journey ahead. Much, much later, as the last Ice Age grew to its height, the mighty Scandinavian icesheet gouged it out from its bedrock, and carried it hundreds of miles, before dropping it, as the ice melted above what is now the Polish lowlands. And there this coral has stayed, in those boulder clay soils, before making its final, and strangest, journey – into this artwork.

252 (18,000 yr)
Boulder clay
Yorkshire, UK

Ice is an extraordinary material. Hit it with a hammer, and it will shatter into a myriad sharp fragments. But pile it up in masses hundreds (or thousands) of metres thick, and it will act like a very stiff fluid, slowly flowing downhill, until it reaches warmer areas, where it melts. As the ice flows, it picks up rock and sediment from the ground surface that it is moving across and can carry it long distances before releasing it as boulder clay. The term 'boulder clay', mind, is now rarely used by the more terminologically pernickety scientists (it is more correct to say 'glacial till'). But, this old-fashioned name nicely reflects the nature of this stuff, which includes huge boulders and rafts of rock, and cobbles, pebbles, sand, silt and clay, generally all jumbled together. Boulder clay had long been noted by the savants of the eighteenth and nineteenth centuries, as something quite different from the more well-behaved strata beneath. For long it was thought to have been formed by a mighty flood, that some saw as the Biblical Deluge. But when travellers began to study the Alps, they saw the glaciers there leaving behind boulder clay, and dared to dream of a yet more terrible vision than a flood – a world buried, not long ago, under a carapace of thick ice. This vision turned out to be terrible, and fantastical – and true.

253 (17,000 yr)
Agathis australis, kauri tree gum
North Island, New Zealand

The massive kauri tree is not as tall as the sequoias of California, but its trunk can reach similar girth, exceeding 8 metres in diameter. It has formed some of the most ancient forests on Earth, ancestral forms stretching back to Jurassic times. It is one of those primeval trees that has evolved means to compete with the newer models of trees, that emerged when flowering plants took over the world. The kauri has gone through a few bottlenecks in that time, though. At the height of the last Ice Age, 17,000 years ago, its range shrank back to just a few tiny areas of northernmost New Zealand – so we can take this layer of dust to include a chip of one of these few survivors – before spreading back again. Now, of course, it is going through a bottleneck that is all too familiar, for it provides good timber. And so, logging of the kauri forests proceeded enthusiastically before some protection was finally put into place. Perhaps the mighty forests can be encouraged to return, for entirely selfish reasons. Kauri forests, with their behemoth-like trees, store more carbon than almost any other kind of forest.

254 (15,000 yr)
Xenarthra: *Megalonyx, Paramylodon*
St Marks River Florida, USA

When faced with the fossil bones of prehistoric animals, we not only wonder at them, but try to work out how they lived, and how they fitted in to the world around them. The majestic giant sloth was one of the largest and most charismatic beasts of the Ice Ages – but what did it eat? Did it, for instance, use its enormous height to reach up into the branches of high trees, to browse on the leaves? Or did it graze on grasses on the ground, like so many other giant herbivores? The modern sloth is a leaf-browser – but then it has little choice, being a tree sloth. The ground sloth, now, did have this choice – but with nothing quite like it alive now, we cannot look for modern comparisons to decide whether it ate grass, or tree-leaves, or both. So where do we look for clues? One scientific team looked at the carbon chemistry of the teeth, to try to distinguish between the two modes of feeding. It was not so simple, because ground sloth teeth do not have enamel, which is the hardest kind of tooth bone and usually the best one to preserve such chemical patterns. But it has two kinds of dentine – and both seemed to tell the same story: *Paramylodon* was mainly a grazer, rather than a browser. That giant head therefore faced the ground, rather than being in the clouds.

255 (13,000 yr)
Archaic-Paleo Native American flint spear projectile point
Texas, USA

It is a beautiful weapon, troublesome as it is to put 'beautiful' and 'weapon' in the same sentence. The flint spearpoints of the Clovis culture (named after Clovis in New Mexico, where they were first found) are leaf-like, and delicately flaked on both sides to give a finely serrated edge, and so may have served as knife blades as well as the tips of spears. They are the sign of a wave of humans moving across North America, crossing the land bridge that existed between eastern Siberia and Alaska, before sea level rose to separate those two landmasses, and migrating southwards. As the Clovis people spread out to fill this new land (they were not quite the first humans to live in the Americas, it now seems, but they were the first to do so in force) they hunted the animals they found, and left a trail of those distinctive, finely shaped spearpoints behind. Around the time of their tenure, some 38 kinds of North American large mammals became extinct. Was it through hunting overkill, a prehistoric blitzkrieg? – the circumstantial evidence is strong, but case is still being argued. And then, a little under thirteen thousand years ago, the Clovis peoples disappeared – or, at least, gave way to a patchwork of other cultures.

256 (12,800 yr)
Sample of 'black mat', cosmic impact layer
Younger Dryas Boundary, West Texas, USA

It was originally a crazy suggestion, or sounded like one, first put forward more than 15 years ago. That, around the beginning of a thousand-year switchback to bitterly cold conditions (called the 'Younger Dryas') as the climate in general warmed from an Ice Age climate to that of the present day, a large comet impacted on or near the North American icesheet. And the resultant mayhem – airblast, wildfires and such – caused that climate switchback and may have led to the extinctions of large beasts such as the mammoth, and to the collapse of the human Clovis culture. The evidence cited for such a science-fiction-like scenario included a 'black mat' layer marking the end of the Clovis culture and the last of many of the megafaunal beasts. The 'black mat', the proponents of this idea said, contained soot, 'buckyball' molecules, high concentrations of iridium, sprinklings of nano-diamonds and other evidence of a huge impact and subsequent firestorm. Well, that set off a scientific firestorm of claims and counterclaims by avid supporters and fierce opponents of this explosive proposal. 15 years on, some of the evidence has evaporated (those buckyballs, that iridium) but other clues have turned up (cosmically derived platinum, a possible crater). That a major meteorite impact might have destabilised an icesheet, to bring about that thousand-year-long cold snap, seems now a touch more plausible.

257 (12,000 yr)
Holmesina septentrionalis, giant armadillo
Florida, USA

This armadillo-like beast was not really a giant armadillo (though it is vaguely related, and it was pretty big), but rather a pampathere (a 'Pampas beast') which evolved a very similar suit of flexible armour. The pampatheres evolved, as the name suggests, in South America tens of millions of years ago, and the shape of their teeth suggests that they grazed on coarse grasses, strengthening the connection with the Pampas regions of that continent. A little less than three million years ago, they crossed into North America, as part of a two-way 'Great American Biotic Interchange' when the Panama Isthmus rose to become a land bridge linking the two continents. This particular kind, *Holmesina*, the bones of which were recovered in Florida, was thus a 'septentrional' (an old-fashioned name for 'northern') species, and comfortable in its new home. Then, like so many other of the large American beasts, it did not survive the double whammy of human onslaught and climate change. It has been gone from the world for some 12 millennia now.

HOLOCENE
11,700 YR-1945 CE

258 (early Holocene, precise age unknown)
Sloth teeth, Suwannee River
Florida, USA

Florida's Suwannee River (and yes, it is the same as the Swanee River, or at least it inspired the old song of that name) has yielded a range of spectacular fossils which stretch back the best part of 50 million years into the past, as far back as to Eocene times. The oldest fossils, which include early whales and impressive shark teeth, are from strata laid down on the sea floor, tectonically uplifted, and now cut through by the river's action. The youngest fossil bones – including this sloth bone in the urn – are from Pleistocene to early Holocene times. They come from sands and muds laid down by an earlier phase of the river, later re-exposed as new meander belts bit into and eroded them. It's the latest part of the kind of long history that can be enfolded within a river. And here, way down upon the Swanee River, as the old song puts it, one can indeed go quite a way 'up and down along the whole creation'.

259 (early Holocene, precise age unknown)
Halite, from evaporated seas and lost lakes
Death Valley, USA

The workings of climate change are intricate. One of most striking signals of the warming of the climate in the far north, as the arid glacial climate of the late Pleistocene gave way to the warm climate of the Holocene, 11,700 years ago, was a great lessening in the amount of dustfall on to the Greenland icecap. This can be detected by drilling into Greenland's ice layers, now a kilometre below the icecap's surface. As the air grew wetter, it became less dusty, and so the snow that fell on Greenland became cleaner. But here in Death Valley, the warming of the climate, and the retreat of the ice in the mountains, meant that the old Ice Age lakes dried up, to form the barren salty expanses that we can still see today. Elsewhere, as we shall see, such now-desert regions carried on blooming for thousands of years. But here, Death Valley has earned its sinister name from very long ago.

260 (Holocene, precise age unknown)
Sponge
St Monans, Scotland

Scotland is one of those northern mountainous places of the world where the history of climate and sea level change – as symbolised by this shallow marine sponge fossil – has been more tortuous than in gentler, warmer parts of the world. As the great icesheets grew and then melted, they took out – and then gave back – enough ocean water to change sea level by some 130 metres. But the enormous weight of ice that was lying over Scotland squashed down the Earth's crust in that region, also by more than a hundred metres – and so the sea encroached upon those ice-depressed mountains. As the ice melted, so the mountains slowly began to rebound upwards again. The shoreline was caught between those two mighty, and continually changing, forces of global sea level and local crustal change; it continually changed its position too, adjusting to whichever was the greater at any one time. And, of course, shoreline animals such as sponges had to migrate too. Now, the ice has long gone, but Scotland is still finishing its slow rise.

261 (Holocene, precise age unknown)
Cat coprolite
Nebraska, USA

It was that extraordinary Victorian-era savant (indeed, both a theologian and a geologian) William Buckland who coined the term 'coprolite' for the fossilised remains of animal droppings. This eminently technical term is – of course – often a source of humour for the younger and more excitable geology students, and one suspects Buckland would have appreciated the jokes too. He was a larger-than-life character, with an iconically untidy and fossil-strewn study, and he reputedly ate his way through the entire animal kingdom then known. Buckland himself developed the use of coprolites with both seriousness and insight. He studied a cave in Yorkshire, Kirkdale Cave, in which a mass of fossil animal bones was buried – said to have been washed in by Noah's Flood, an idea that Buckland himself at first supported. But then he saw that many of the bones had been chewed, and that there was also a great deal of what he recognised as fossil hyena dung on the cave floor (using impeccable scientific technique, he made comparison with hyena droppings from a local zoo). So Kirkdale Cave, he realised, was not a Noachian flood disaster site, but an ancient, long-used hyena den: an interpretation that was a major step in understanding of the prehistoric past.

262 (Holocene, precise age unknown)
Deer antler
East Coast, USA

In the Holocene, we are so close to the present, geologically (even if it seems almost infinitely far away in terms of human lifetimes) that when we find a fossil, it will often seem familiar rather than a petrified primeval relic. Indeed, the word 'subfossil' is often used for such bones and shells, typically extracted from their shallow burial sites in peat bogs or river sands. The bones will mainly be of familiar creatures, such as deer, pigs, and rabbits, and they are usually still porous, rather than being infilled with solid mineral. It is a different kind of palaeontology, and also one which, for many parts of the world, does not represent a pristine, unaltered environment. For, humans by now had spread to many parts of the world, and to begin to change it, by axe, spear, and fire. Early in the Holocene, their footprint was still very light by comparison with today's wholesale global environmental changes. But this deer, when it lived, likely already had learnt to fear the two-legged hunter that could kill from a distance.

263 (Holocene, precise age unknown)
Horse vertebrae
Texas, USA

The horse plays such a central part in North American culture that one could be forgiven for thinking that it had always been an integral part of that continent. And, geologically speaking, it has been, for North America was for long the sole cradle for the long and complex evolutionary history of the horses, from Eocene times onwards. Horses only spread to the Old World at the beginning of the Pleistocene Ice Ages – and a good thing too, for the longevity of this ancient line. For, after some 50 million years of continuous evolution, the horse became extinct in North America some 10,000 years ago, early in Holocene times, as part of that great wave of megafaunal extinctions that spread across the continent in those times. Then, human hunting may have been the culprit, while it was humans who, much later, re-introduced European horses to America with the voyages of Christopher Columbus and Hernán Cortes.

264 (Holocene, precise age unknown)
Sus scrofa, wild boar
Romania

One of the great symbols of the world as a place of infinite resources is in the high adventures embarked upon by Asterix and his merry band of fellow Gauls, where the derring-do is punctuated by frequent feasts where wild boar invariably takes centre stage of the menu, with – equally invariably – the lion's share being hogged by that amiable gourmand Obelix. Intelligent, hardy, adaptable, wild boar have managed to survive the depredations of the many real-life Obelixes who have hunted them throughout the Holocene, to retain a good deal of their native range in Europe and Asia. True, they have been hunted to extinction in a number of regions, such as the British Isles and Scandinavia, but even here, there have been programmes to re-introduce them. And recently also, they have become a successful – and hence troublesome – invasive species in the Americas. It has been a survivor in the increasingly human-dominated world since the last Ice Age receded.

265 (Holocene, precise age unknown)
Seal bone
Belgium

The seals, as animals of the sea, were largely spared the blitzkrieg of human hunting that rolled through the world from about fifty thousand years ago, and peaked some ten thousand years ago, as the Pleistocene ice gave way to Holocene warmth. Indeed, early Holocene times were likely boom times for these animals, as they recovered from the ice's squeeze on their living space. Evidence of humans coming into their lives dates back some four thousand years, as the Inuit peoples of the far north began to intertwine their lives with those of the seal. This association, and the small-scale harvesting it was based on, lasted for thousands of years – and in itself could have lasted almost endlessly, as a classic example of sustainable existence. In recent centuries, as we know, these ancient seal hunts have been overtaken by industrial hunting that grew to a gigantic scale. The Inuit lifestyle, and seal harvesting, still goes on – though now is threatened as our industry, writ more widely, warms the climate and shrinks back the ice.

266 (Holocene, precise age unknown)
Beaver, vertebrate
Colorado River, USA

A beaver bone must, of course, come from a river. These famously industrious animals have long been a part of nature mythology. To a geologist, their actions go beyond an addition to the variety of a river landscape. They literally build the ground beneath our feet. The dams they build with such genetically programmed skill hold back not only water, but the sediment carried by the water too, which settles to build up thick layers of sediment that drape, and soon make a large part of, the foundations to the valley floor. The scale, and architectural pattern, of such landscape construction can be revealed by the X-ray eyes of ground-penetrating radar, and this nigh-well magical technology can reveal, too, how the fate – and shape – of the land has long been intertwined with that of the beaver. Through most of the Holocene, many valleys were literally beaver-designed, until the hunting began in earnest, when the dams, and this mode of landscape construction, fell into disrepair. Now there is some protection for what is left of the beavers, we might see this ancient mode of landscape design begin to return.

267 (Holocene, precise age unknown)
Ovis aries jaw
Romania

The sheep, as we know it, has a history that more or less coincides with that of the Holocene, for it has been domesticated for about that long, to supply the endlessly growing human demands for wool and meat. Its wild ancestor, the European mouffon – which one can still see in Corsica and Sardinia – is a beast that evolved naturally for mountain life, as a lean and rangy animal, with short, rough brown fur. Those millennia since have been used to breed the familiar white and woolly animal and its many varieties, to spread it around the world, to develop sophisticated skills, both human and canine, to maintain its flocks, and, eventually, to grow its numbers hugely: there are now something like a billion sheep in the world. In these modern times, even as their numbers grow, the demand of modern agribusiness for uniformity means that many of the old domestic varieties are in danger of disappearing. The Holocene, in that sense, was a golden age for sheep diversity – albeit a kind of diversity made by humans, for human purposes.

268 (early Holocene, precise age unknown)
Phanourios minor, Cyprian hippo
Cyprus

Islands do strange things to animals – and they can do it quickly, in a kind of evolution that can sometimes only take some thousands, rather than millions, of years. In particular, islands can be home to giants – think of the ferocious Komodo dragon, which is the world's largest lizard – or dwarfs. The hippo of Cyprus, that became extinct sometime near the beginning of Holocene times, perhaps 10,000 years ago, was such a dwarf: smaller than the average pig – yet, in its own time, it was the largest animal on Cyprus. The reason for this downsizing can simply boil down to food supply, with some islands unable provide enough nutrition to sustain full-sized animals. This hippo is in good company, globally speaking. The island of Flores, part of the Indonesian chain, for instance, once supported a population of pygmy humans, *Homo floresiensis*, aka 'the hobbit', not much more than a metre tall (and for good measure a pygmy elephant also used to live on Flores). The last mammoths of all, that lived on Wrangel Island until mid-Holocene times, were tiny too.

269 (10,000-2,000 BCE)
Native American obsidian scraper tool set
Mojave Desert, USA

It is extraordinary how the history of the Earth can entwine, in the most specific of ways, with that of the humans living on it. Obsidian has long been prized by humans, almost certainly from before the time of our own species, for the way its particular combination of hardness and brittleness, allows – if skilfully shaped – tools of marvellous sharpness to be fashioned. It gets these qualities from a fiery origin, as stiff, silica-rich lava oozed to the surface, its viscous nature (from a kind of polymerisation of those silica molecules) preventing the formation of crystals as it froze. It is, therefore, a frozen liquid – a natural glass – rather than being the usually crystalline kind of solid lava. Native Americans might have observed the connection between this rare and extraordinary kind of rock, and the nearby mountains that, now and then, exploded into fiery life. And, once they found an obsidian layer, they would learn to trace it across country, and perhaps underground too. Part of the birthplace of geological science lies among such ancient endeavours.

270 (10,000-8,000 BCE)
Upper Paleolithic Levallois flint tool
Doggerland

Doggerland has attained an almost mythic status as a prehistoric landscape, an 'Atlantis of the North Sea', now drowned, that, for a few thousand years at the end of the last Ice Age, was inhabited by our Mesolithic ancestors, and grazed upon by aurochs, reindeer, and wild boar. Remarkable as it was, it was just part of a lost world of landscapes worldwide that had been exposed when sea level was up to 130 metres lower than at present, at the height of the last Ice Age, and that was progressively submerged, over more than ten millennia, as the great icesheets melted to give their water back to the oceans. Going back through time, Doggerland – and its global equivalents – has emerged and been submerged repeatedly, as the glaciations and warm interglacial phases of the Ice Ages succeeded each other, more than fifty times in the last few million years. The latest part of this latest version of Doggerland has become notorious for one final catastrophe: being swept, a little over 8000 years ago, by a mighty tsunami, as part of Norway's continental margin collapsed into the sea. The animals and hunters did come back to the devastated landscape, but only briefly, for the sea continued to rise until it reached its present level, some 7000 years ago. Since then, sea level has remained much the same, to give Holocene times a stability which must have seemed eternal to coastal human communities, once the memory of an ever-advancing sea had faded. And, now we must get used, once again, to an endless, progressive inundation, this time one of our own making.

271 (7,000 BCE)
Thalassina anomala, mud lobster
Darwin Australia

This mud lobster, *Thalassina anomala*, from Gunn Point in northern Australia is a crustacean with a lustrous carapace and ferociously strong pincers. It still lives in the coastal waters, while its ancestors have left many of their skeletons in strata that date back to 7000 years ago, when sea level finally climbed to its present level, following the final melting of Pleistocene ice. This was several thousand years after the formal end of the Pleistocene as we classify it today, and also several thousand years after the climate warming that set this great melt in train: it's a measure of the difference in timing between cause and effect, when large parts of our planet's machinery interact. These lobster-bearing strata – ancient to us and already quite hardened, but laughably young in relation to Earth history – can be seen when the tides wash away the modern beach sand that usually covers it, and dug into to extract these petrified joint-legged treasures. *Thalassina* is in particular a creature of coastal mangrove swamps – still present around Gunn Point, and so, from the evidence of these fossils, part of the early Holocene community there too.

272 (7,000 BCE)
Hemispherical *Manicina areolata*, coral
Palm Beach Florida, USA

Coral reefs flourished in the Holocene, after surviving the rollercoaster changes and switchbacks of the Pleistocene Ice Ages. This was not so much because of the temperature changes, for the reef-building corals generally live in the tropical and subtropical parts of the world; these were squeezed in glacial times, but retained much of their warmth, much as did the Carboniferous coal swamps in those much earlier ice ages. Rather, it was the many large rises and falls in sea level that challenged their existence: as sea level fell, the reef areas became dry land and their corals died, with new coral communities doing their best to follow the shoreline out to sea; and as sea level rose, the corals both migrated back inland to follow the advancing shoreline, and also built upwards towards the sunlight. (This adjustment didn't always work – if sea level changed too quickly for the corals to keep up, a reef could be killed off altogether.) Within its enormous, ancient collective skeleton, therefore, a coral reef keeps an archive of the ups and downs of sea level, that geologists now seek to decipher. The last seven millennia have allowed corals to adjust to a stable sea level, and to thrive. Now, of course, the challenges to them are beginning again.

273 (4,500-2,500 BCE)
Neolithic flint hammer
UK

It is a material culture that goes back more than two million years – and several human species. Its representation here marks the end of a phase of slow – almost glacially slow – evolution of stone technology. This technological evolution would soon speed up, as humans learnt to made tools from a range of other materials. This is another intertwining of histories from deep time and shallow time. Flint – as we saw in deeper layers of this urn – is the result of a phase when the Earth's ocean floors began to form more rapidly, to warm the climate and create an ocean in which Chalk oozes rained on to the sea floor. Within these layers of ooze, some kinds of silica-based fossils, such as sponges, dissolved and then re-formed to make flint nodules. Several tens of millions of years later – and in a much cooler climate – humans learnt to excavate this tough, splintery material, and fashion it into tools. The likes of this flint hammer may not be as sophisticated as a ballpoint pen or mobile phone – but there is a geological simplicity and durability here that can outlast many of our modern creations, and that may yet be carried into the far future.

274 (4,400-4,200 BCE)
Neolithic Vinča solar amulet
Serbia

The Vinča culture of south-eastern Europe was, one might say, a pioneering one of the human enterprise. People gathered together in larger numbers, forming networks that extended widely across the region, with some individual settlements having populations of up to a few thousand. Its culture, it has been suggested, was matriarchal. The people domesticated plants and animals, made beautiful 'Dark Burnished Ware' pottery, and were the first to mine and smelt copper. They made clothes too – none have survived, but their images remain on some figurines. And, they drew symbols, as on this amulet, that might be an early form of written language, although their meaning remains mysterious. The culture died out about 6000 years ago; exhaustion of the soil may have been one reason, and the arrival of warlike invaders another. It may have been some kind of golden age, perhaps, that lasted for some 1500 years; it seems to have been a relatively peaceful one, too, before the network unravelled.

275 (6,000-4,000 BCE)
Neolithic bone, reindeer antler chisel
Europe

Bone was another kind of technology used as humans explored the world around them in Holocene times. Frail and primitive as a tool, one might think, but it could accomplish marvellous things. Four thousand years ago, such bone tools, together with rocks for pounding, were used to find and dig out copper ore from Parys Mountain, in Anglesey. The copper deposit there is so complex that modern geologists scratch their heads over it – and yet these early peoples dug down tens of metres with this technology, to find the metal that they could then use to devise a new generation of tools. It was part of the beginning of the ratchet-like process by which one technology is used to make the elements of another. This process has, by now, mushroomed to entirely reshape not just our own world, but the surface of the planet, in a giant skein with millions of connections. Back then, the links in the incipient technological chain were much more physically hard-won – but it was easier to see how the world was changing.

276 (3,400–2,250 BCE)
Ancient jade cong with carved eyes, Liangzhu culture
China

There is something about human sophistication – if that is the appropriate word – that, as human societies began to build complex civilisations in Holocene times, brought something new and bizarre into the world. This was a devotion of immense effort and skill to make objects that bring no practical use. Jade is a mineral (to be precise, it is either of two minerals, jadeite and nephrite) that is notoriously difficult to work. And yet, not so much in spite of this as *because* of this, it has become highly prized and sought after in many cultures, as the raw material to painstakingly build beautiful but useless objects. This 'cong' of ancient China – a carved, decorated prism of jade with a circular hole – is a prime example. Many have been found at archaeological sites, but their specific purpose remains unknown. The best bet is that – being ferociously difficult to carve – they were made to increase the prestige and influence of the owners. It's a motive force not to be underestimated as regards its capacity to shape human society – and then, somewhat later, refashion the planet.

277 (3,300-2,200 BCE)
Ancient Indus Valley terracotta painted bull idol
South Asia

Humans have always co-existed with other animals. For most of the history of our species, and for all of the history of other, earlier species of human, we were simply one kind of animal amongst many other – with many of those other animals being larger, stronger, fiercer and faster than humans were. Survival meant adjustment to these realities, and those cave paintings of Pleistocene times suggested some kind of identification with, and awe for, the wild beasts which were in equal measure predator of and prey for our ancestors. As the power of organised humanity grew in the Holocene, so the balance shifted, and animals – especially the powerful ones – became things to subjugate, not just to provide meat and milk and do work for us, but to proclaim our newfound power over the rest of Nature. Was this terracotta bull idol, now ground up here, carved as a power to wonder at as an equal in nature, therefore – or was it shaped as a reminder that we now possessed this power, to subjugate other living beings? It is a key distinction in the history of our relation to the rest of the biosphere.

278 (3,300-2,200 BCE)
Ancient Chinese Neolithic looped jar, Majiayao culture
China

How long does the worldwide spread of transformative new technology take? And a jar is transformative, much as was the evolutionary origin of the egg, back in Carboniferous times, that enabled reptiles to venture farther from water than amphibians were able to. With a pottery vessel, one could carry oil, or water, or wine while travelling, and store them during hard times. And pottery is an invention that also has geological overtones, in humans learning to mimic the natural lithification and metamorphism of mud: almost certainly by accident at first, and almost certainly this technology was independently discovered at different times in different parts of the world. China is where the earliest known pottery vessels are recorded, twenty millennia back in the depths of the Pleistocene Ice Ages, so this example is only a quarter as old. But it is only half as old as the earliest pottery known from Eastern Europe, and only a little older than the earliest British pottery vessels.

279 (3,100-2,900 BCE)
City seal from Jemdet Nasr, now Iraq
Mesopotamia

We evolved as a succession of human species, over millions of years, to live in small groups of hunter-gatherers: perhaps numbering a hundred or two hundred, where everyone knew everyone else, with the same kinds of tasks shared out. And, for some 97% of its existence, our own species lived like that too. But for the last 3%, humans began to settle, and to aggregate in larger numbers, to form villages, then towns, then cities, sustaining themselves by crops grown in fields and from the domestication of animals. The development of civilisation, it has been called, and it more or less coincides with the Holocene. This step has been thought to be, by some, humanity's greatest mistake: the exchange of a life of uncertainty but relative freedom and leisure, for one that could feed and support larger – ultimately, much larger – numbers of humans, but one that subjugated most of those humans to a lifetime of toil and servitude. The seal of one of Earth's earliest cities, now held in this layer of the urn, neatly symbolises this great transition. It would go on to have enormous significance for subsequent generations of humans and, eventually, the planet itself.

280 (3,100-2,900 BCE)
Terracotta Holy Land vessel
Israel/Palestine/Jordan

Around half-way through the time of the Holocene, the ability to make a vessel that might store water took on added significance. For the Holocene, at a first approximation, is a time of globally stable climate that has allowed human civilisation to develop. But, at a second approximation and at a regional level, climate did change – not in such a dramatic rollercoaster fashion as during glacial times, but nevertheless quite significantly enough to affect the emergent human societies. Thus, the early part of the Holocene in the Middle East and Saharan Africa was a time of wetter climate than today, in fertile, 'pluvial' times, when life, including human life, flourished. And then, mid-way through the Holocene, the climate of this broad region – because of slightly different sunlight patterns as the Earth's spin underwent one of its slow, regular changes – grew drier (while that of northern Europe, in turn, grew wetter). Water in the Middle East, then, slowly went from being abundant, to becoming a scarce and fickle resource, that required much ingenuity and technology to manage. This terracotta vessel may be counted as one infinitesimal part of coming to terms with new and more difficult times – that were nevertheless only *regionally* more difficult times. The planetary climate system overall remained, then, firmly on an even keel.

281 (3,000 BCE)
Ancient cuneiform
West Asia

It is easy to fossilise shells, bones – and even flint implements and pottery. But how does one fossilise ideas, instructions, or stories? That kind of petrifaction did not take place for four and a half billion years of our planet's history. Then, one might say, its beginnings might be found in the cave paintings of our Stone Age ancestors, where it seems that not only the form of the animals that these early humans lived among were captured, but that these pictures also contained narratives, then of great importance, though now difficult for us to decipher. After that, the pictures became more stylised, more of a code to express thoughts and utterances – and written language emerged. Now, information of different kind – for the collection of taxes, or the glory of some emperor, or a heroic tale – could be set down and transmitted from one person to many others. Writing, thus, allowed the kind of dissemination of information, and organisation, that was needed to allow a complex organism such as a city to grow without disintegrating. And over time, it allowed ideas to be preserved and transmitted from one generation to another, intact and without the kind of losses and mutations that take place in spoken transmission. It was a giant step in humanity's capacity to take over the world.

282 (ca 1000 BCE)
Elephant bird, *Aepyornis maximus*, sub-fossil
Madagascar

Looking at a sparrow or chaffinch in the garden, it is hard to think that these, biologically, are dinosaurs, the kin of the brontosaurs and *T. rex*. But looking at the remains of an *Aepyornis maximus* of Madagascar, these connections are easier to imagine. More than three metres tall, reaching half a ton in weight, this 'elephant bird' laid eggs that could be more than a metre in circumference. For some, it is the origin of the legend of the roc, which Sinbad the Sailor encountered in the *Arabian Nights*. *Aepyornis* was not quite the biggest bird known to have lived: this was its close relative, the yet heavier *Vorombe titan* (which until 2018 was called *Aepyornis titan*, so it is a close close relative). These monstrous birds died out comparatively recently, likely less than a thousand years ago. Humans are implicated, but in a complicated way, as humans and the elephant birds seem to have coexisted for quite some time before the latter perished, likely through some combination of hunting, eating those gigantic eggs (a single one of which could feed a very large human family) and the spread of diseases. It was one more giant lost to a world becoming ever more human.

283 (2,000 BCE)
Bactrian polished stone cup
Ancient Iran

As the biological world on land slowly diminished, as losses accumulated among the giant beasts of the animal kingdom, so the growing human world became more complex, and more powerful. This stone cup is from a Bronze Age culture that spread over what is now Iran, Afghanistan, and Turkmenistan. It used to be called the Oxus Civilisation, though now is more properly, if less poetically, termed the Bactria-Margiana Archaeological Complex. The artisan who shaped and polished this cup would have been one kind of specialist – who would know which kind of rock to choose for which purpose – and would have worked as part of a society that included specialists in metals, who could fashion tools and ornaments from copper, bronze, gold and silver, of farmers who grew crops and domesticated animals, of architects and builders who could construct cities, and soldiers who could defend them (and attack others). It was just one of many such empires that grew out and shrank back as the long, more or less stable warmth of the Holocene continued, to incubate the kind of human world that is recognisable to us now.

284 (300 BCE)
Ancient Egyptian bust
Ancient Egypt

Of the human empires that waxed and waned as the millennia of the Holocene succeeded each other, that of Ancient Egypt was one of the most long-lasting. It must have seemed, to any person living within it, ageless and never-ending, with a kind of stability and durability that we can now scarcely imagine. When this bust was made to celebrate just one of these myriad human lives, the pyramids of Giza had already dominated the skyline for some two millennia. Various invading powers had come and gone, of course – the Nubians, the Assyrians, the Persians and Alexander the Great's Macedonians, and it would be less than three centuries before Cleopatra's downfall, and takeover by the Romans. But the location and rhythm of life, dominated by the life-giving Nile and its seasonal flood patterns, continued. Earlier in the Holocene, that life had spread across the whole region, in those wetter times of the 'pluvial' periods. But then the rains dried up, and most human life contracted to that narrow green strip of the river valley and delta, amid wide, barren expanses of arid desert. That narrow green strip is still the focus of Egyptian life, a measure of how the fundamentals of life still constrain us, for all our sophistication today.

285 (300 BCE)
Ancient Greek Hellenistic pottery dish
Ancient Greece

There is more to life than survival, than the struggle for food, shelter, and land – and more to the Earth than providing a source of all that sustains us. The bowl that now forms this layer of dust is separated only by a matter of decades from the lives of Democritus and Aristotle, whose great explorations were not for silver or gold, or for land and power, but into the nature of the Earth and of the life that surround us. Their influence would have been deeply felt, still – and indeed it has persisted to the present day. Democritus, for instance, proposed that all around us is made of tiny, indivisible, indestructible particles called atoms. And Aristotle, among his accomplishments in poetry, logic, meteorology, geology and much else, made a classification of the whole of life from worms and insects to fish, reptiles, birds, mammals – and humans. Aristotle and Democritus were among the founders of what we might call the scientific method, in which one makes logical deductions from the evidence we see of the world around us, rather than blindly accepting the opinion of some higher authority.

286 (300 BCE)
Phoenician pendant
Fertile Crescent

As one follows human history across the dozen millennia of the Holocene, one comes across the names of many fabled empires. That of the Phoenicians is certainly one, loosely defined as a people who mostly occupied what is now Lebanon, but who gained their power and their reputation as seafarers who built up a great maritime trade network across more than two millennia. The pendant from their culture contained now in this artwork catches them at the end of their history, more than a thousand years after the peak of their power, and after they had been conquered, brutally and bloodily, by Alexander the Great and thus 'hellenised'. Soon after, they became part of the Seleucid kingdom, before becoming a Roman province, and yet later falling within the Muslim Arab sphere. There are many lessons to be drawn here. One is how the use of the sea allowed human networks to grow, spreading links across large regions of the world: a prelude to today's globalisation. The other is about the divisions that repeatedly arose within humanity, to create warring factions that vie, murderously, over land and over peoples. The Phoenicians seem to have been largely active in the first endeavour, and victims of the second. Much of human history in the Holocene has been driven by how these two opposed trends played out, against a backcloth of an Earth that, in those days, could absorb the hurts involved, and heal in time for the next empire to grow.

287 (100 CE)
Nabatean terracotta bottle
Northern Arabia/Southern Levant

As climate changes for the worse, one response is to retreat towards areas that still provide a comfortable life, as the Egyptians did as the deserts grew around them, and only the Nile valley remained lush and fertile. Or one can adapt and learn to live with the difficult conditions. This was the path followed by the Nabateans, a people who lived around what is now Jordan, who could survive in the barren deserts and mountains, and skilfully harvest rainwater to develop agriculture in these harsh conditions: the terracotta bottle that now lies in this urn layer is an apt symbol for their culture. They were great traders too, and built a city to control their trade routes that now has a more famous name than theirs. This was Petra, that was called a 'rose-red city, half as old as time' in a poem by the Victorian cleric John William Burgon. Burgon did not mean to exaggerate. He was a fundamentalist, who believed in the literal truth of the Bible, both Old Testament and New, and in an Earth that formed in 4004 BCE. So, Petra – founded a thousand years BCE – was, quite literally, exactly half as old as his conception of time. Burgon would have been distressed to learn that the sandstones out of which Petra is carved date from Cambrian and Ordovician times and so approach half a billion years old, while the Earth is ten times older yet. Petra is thus less than a millionth as old as time, a thought which might give it more grandeur, not less.

288 (100-1,600 CE)
Ancestral Pueblo pottery shard
Native America: Arizona, New Mexico, Colorado, Utah

For most of the history of our species, the fiercest predators of humans were other kinds of animal: lions, panthers, snakes – and of course pathogenic microbes, albeit then invisible and unsuspected. Then, as humans grew more numerous and more powerful, the fiercest predators were other humans, a situation that has remained to the present day (along with the microbes). Much of human life then revolved around trying to protect against that danger. The ancestors of today's Pueblo peoples were the Ancestral Puebloans of North America's arid South West region. The Ancestral Puebloans took to building their homes within high, vertical canyon cliff faces, some approached along the narrowest of ledges, where a slip meant certain death: magnificent protection from attackers, yes, but also a hazardous journey that all must have regularly made, including the children and the old. The Ancestral Puebloans survived for many centuries, built elaborate constructions, made richly decorated pottery, made pictographs, were fine astronomers. But, sometime around the thirteenth century CE, something went dreadfully wrong. That civilisation seems to have imploded and disappeared. What happened? There had been a centuries-long drought, certainly, ratcheting up stress on already difficult lives. Massacres took place, even cannibalism, though it seems unclear whether the violence came from outside, or from within, the community. Perhaps, one can only live a life on the edge for so long.

289 (100-300 CE)
Ancient Roman stone weight
Ancient Rome, Italy

In establishing a civilisation based on trade, and buying and selling, one of the basic systems that needs to be put into place is a series of measures: of length, of area, and (especially) of weight. The Roman system of measures was elaborate and sophisticated, and derived from the systems used by those previous trading empires, of the Greeks and the Egyptians. The *uncia*, for instance, was the equivalent of our ounce (to be exact it was 0.974 of an ounce – to show the exactitude which had already developed). 12 *unciae* formed a *libra* (i.e. a pound), though there were names too for *uncia* multiples; thus, seven unciae formed a *quincunx*, and eleven a *deunx*. The uncia was elaborately subdivided, too. For example, one one-hundred-and-forty-fourth of an uncia was a *siliqua* (equivalent to our carat), and one twenty-fourth was a *scrupulum* (equivalent to the scruple, a measure once used by apothecaries). So, one should not think of the stone measure as something rough and approximate, even if it is two millennia old. It would have been finely engineered – and its use observed with hawk-like attention.

290 (200-400 CE)
Gandhara schist head
Ancient Indian subcontinent

As different empires grew through the Holocene, and intersected each other, either peacefully through trade, or violently through war (or both) then their various characters mingled, to create new forms, in the resulting human cultures. One of the clearest ways of seeing this is through symbolic forms of expressions, through the art made by peoples. Gandhara, in the first few centuries CE, was a region (now parts of Pakistan and Afghanistan) that lay at the hub of the Silk Road trade routes. Influence came from the East, and the empires of Asia, and the West, from when Alexander the Great's empire grew. The heads sculpted, in this cultural cauldron, by the Gandharan artists combined classical Roman/Greek style with Buddhist and Indian subjects, such as the Bodhisattva, a deity representing altruism and compassion. The Buddhist timescale is long and would easily encompass the schist out of which the head is carved, a rock forged in the depths of the Himalayan mountain belt as it began to grow, fifty million years ago. It's another kind of intersection, to preserve within *Requiem*.

291 (205-220 CE)
Glazed artist's palette, Han Dynasty
China

Visual art of some form or other has been present ever since what has been called 'culturally modern humans' emerged some 50,000 years ago, that is five-sixths into the palaeontological span of the fossil bones assigned to *Homo sapiens*. In the beginning, with the cave art epitomised by Lascaux and Altamira, it seemed to reflect how human life was bound up with the great beasts of the Pleistocene. Later, it dwelt more on human life – and human vanities too. For the mighty Han dynasty of China of some two millennia ago, it took on a more strategic, even political, role. Following turmoil and civil war, the Han established control of an area which in effect defined what China was to become, and what it remains today. The capital of this realm, Chang'an, was the only city on Earth to then-rival Rome in size and splendour. Architecture flourished as did science (including, for instance, the invention of the seismometer), literature, philosophy – and art. This new empire held within it disparate peoples, cultures, customs, and the Han rulers saw art as one means of spreading a sense of a shared life within their new realm. Scenes from everyday life were a focus, and portraits of the wealthy and powerful, and famous figures from history (the classic landscape images were not to become common until several centuries later). Thus, the artist who used this palette worked within a world in which the arts were prized and valued – but where they also served a wider purpose in ordering the emerging world of the Holocene.

292 (300-500 CE)
Byzantine Terracotta infinity line storage container
Europe

Only the western part of the Roman empire collapsed in the fifth century CE, amid internal power struggles and waves of barbarian invasions. The eastern part, that of Byzantium, was to persist for another thousand years, for most of that time as the greatest power in Europe. It is a fabled name – but one invented after the empire eventually collapsed, as it fell to the Ottomans; it's a convenience for historians, for this version of the empire was as much influenced by Greek as by Roman culture, and its religion – another means of establishing identity among human cultures – was Eastern Orthodox. While this eastern empire persisted, though, its citizens generally called themselves Romans, living in Romania – though that has only a glancing connection with modern Romania (a nineteenth century invention, with its territory in the Middle Ages only lying at the fringes of Byzantine influence). The mutation of names and entities of the human societies through the later Holocene is enough to make one's head spin – but the terracotta pot here at least represents one of the larger and more durable parts of this merry-go-round.

293 (300-700 CE)
Teotihuacan adorno xico artifact, with ceremonial bars and bundled feathers
Mexico

Well before the Americas were colonised by Europeans, mighty kingdoms grew in that part of the world too. Teotihuacan was a city in what we now call Mexico, at a time that we now call the first half of the first millennium CE. It is said to have been the largest city then in the Americas, and the sixth-largest in the world, and it included the monumental Pyramid of the Sun, the third largest pyramid on Earth. Teotihuacan shows both the power of collective human society, and its fragility. It collapsed in the sixth century, likely by popular uprising rather than invasion, as the buildings destroyed were mostly those of the city's ruling elite, and not of the general population. The trigger may have been a brief, savage cooling event across the northern hemisphere in 535-536 CE, bringing crop collapse and malnutrition in its wake. That in turn was likely the result of ash injected into the stratosphere by a volcanic super-eruption, more powerful than that of Krakatoa, and perhaps even that of the 1815 eruption of Mount Tambora, that infamously caused a deadly and miserable 'year without a summer'. Ice layers from 535-6 CE on Greenland are rich in sulphate, a clue to intense volcanic activity somewhere in the world. But where? That is not yet clear – the Ilopango volcano in El Salvador has been mooted, and Iceland too. No matter. The reach of a super-volcano is huge, and nowhere is safe – not even the culture that built the Pyramid of the Sun.

294 (500-800 CE)
Late Roman glass flask
Ancient Rome

A solid that is as hard as rock but as translucent as water is so useful – and so beautiful – that it is one of humanity's enduring inventions. There is natural glass, of course, such as volcanic obsidian, but this is usually so dark and full of impurities that one could not make, say, a window out of it. But glass is tricky stuff to make, and it needs both expertise and technology. It is mostly silica, but pure silica (the mineral quartz in nature) only melts at very high temperatures, beyond the reach of a normal fire. One can add sodium carbonate to quartz and it will melt at a lower temperature, but the resultant glass will dissolve in water – so to resist that, lime is added, and magnesium, and alumina. A complicated recipe, therefore, though one that had been worked out in Bronze Age times, then lost during times of turmoil, then re-invented and developed in different parts of the world. By Roman times, glassmaking became sophisticated – an expertise lost locally as Rome fell, but that re-emerged elsewhere, and carrying on in the Byzantine continuation of the Roman Empire. It is hard to extinguish such a useful technology, once invented.

295 (500-900 CE)
Mayan animal-headed terracotta ocarina figurine
Central America

Music is hard to preserve – at least it was until the written code of crotchets and quavers that can be put on a stave was invented, and later, in modern times, the gramophone record. But musical instruments can be robust and survive the musician that used them by centuries or millennia. There is little preserved, for instance, of how music was played, and for what purpose, in the sophisticated and diverse Mayan culture of central America; the Spanish invaders who terminated that culture were more intent on looting wealth than on anthropological recording, and destroyed almost all examples of books written using the sophisticated Mayan language. But archaeologists have found many examples of Mayan ocarinas – small wind instruments often made in the shape of different kind of animals – so music clearly did play a role, but further speculation is all too open-ended. One can say that timbre and rhythm were likely more important than pitch, for terracotta is too difficult to shape to allow precise tuning. Beyond that, Mayan music remains mysterious.

296 (800-1200 CE)
Hohokam stone pestle grinder
Native America

The Hohokam peoples made a life in the harsh conditions of the Sonora Desert of North America for more than a millennium, using this unpromising terrain as best as they could. To allow farming, they needed to become engineers first, constructing complex canal networks for irrigation. They carefully balanced the canal gradients, keeping these to about a metre each kilometre, so as to minimise the twin problems of siltation and erosion, and constructed weirs to help control the flow, with constant maintenance needed to prevent the canal banks from degrading. The Hohokam pestle would have ground the fruits of this labour, likely maize – already then a staple crop – to provide flour to trade, or to store for the lean times. Some of the Hohokam canals have been restored for use today, although they are now maintained by lining them with concrete. That makes for an easier life now, for sure, though one suspects that this solution is not as sustainable in the long term, as was that ancient, painstaking construction.

297 (900-1100 CE)
Medieval Viking coral beaded necklace
Denmark

One of the most fundamental patterns of the Holocene is the human migration across the planet, to eventually reach pretty well every part of it, eventually including both poles and the equator – a most unusual property of a biological species, most of which typically are adapted to a particular set of conditions, whether geographic or climatic, or (usually) both. The Vikings classically exemplify this wanderlust, with their iconic seagoing voyages, the personifications of bold marauders from afar. Their reality is terribly difficult to comprehend. When one looks at preserved Viking ships, such as Oslo's *Oseberg* and *Gokstad*, it is hard to take in that such finely crafted but frail and open vessels could carry human beings – and keep them alive – in voyages across thousands of miles of rough seas to Britain, to Greenland and, as we now know, even to North America. The voyages of the Pacific peoples to reach many isolated islands of that wide ocean spark similar feelings of awe. Many must, of course, have perished in such voyages into the unknown. This kind of determined, perhaps obsessive, wanderlust is one of the forces of nature – of human nature – that changed the face of the planet.

298 (960-1279 CE)
Shipwrecked urn, Song Dynasty
China

While Europe slowly grew in the Middle Ages – not long after, say, the reign of Alfred the Great and his defeats of the Viking invaders – there was a powerhouse to the east, of which most Europeans then were scarcely aware, if they were aware at all. The China of the Song Dynasty had a gross domestic product estimated to be three times the size of all of Europe's, and among its inventions were catalysts of wealth and power such as paper banknotes and gunpowder, and of geographic exploration such as compasses with magnetised iron needles. It grew for three centuries, before falling to Kublai Khan, legendary grandson of the yet more legendary Genghis Khan. The shipwrecked urn now preserved here – a millennium or so separates the two – is part of this societal growth, and testament too to the ever-present dangers inherent in maintaining lines of communication, and of trade, within the Medieval world.

299 (1009 CE)
Piece of Durham Cathedral
Durham, UK

Durham Cathedral may be considered as an ancient masterpiece, a gem of Medieval engineering, its construction beginning more than a thousand years ago. There is ancient and ancient, of course. Much of its fabric took its form some 310 million years ago, as a river delta built out over a truly primeval tropical jungle. The river sands, now petrified, have the form of a sandstone bed – the Low Main Post, the workers called it – that was quarried to build the cathedral (you can see outcrops of it, if you take a short walk from the cathedral). The thick coal seam – the Durham Low Main, the compressed remains of that jungle – beneath that sandstone may have been dug out, too, as fuel for fires of generations of bishops and parishioners. But not too far: with no steam engines to pump water out then, one could not mine too deeply. It was a feature of that late Holocene time that one could take just a little from the very deep past, without changing the order of the world. Was an idea of time immemorial somewhere in there, perhaps? That time has moved on rather more quickly since then, alas.

300 (1200 CE)
Islamic Seljuk oil lamp
Middle East

When the empire of Byzantium came to an end, it was the Seljuk people, Sunni Muslims from what is now western Turkey, who wrested control from it, conquering Baghdad and building their own huge empire that stretched to the Hindu Kush in the east, and the Persian Gulf in the south. Its history began and ended, less than two centuries later, in warfare, and was punctuated by military campaigns too, as the Christian Church sought to recover their Holy Land by launching both the First and the Second Crusades against the Seljuk Empire. As for much of Holocene time, the history of humanity can seem to be never-ending bloody struggles for power and for land, a seeming common thread for our species. This oil lamp, let us hope, served to light the lives of people in one of the more peaceful interludes, amid that endless strife.

301 (1500 CE)
Taino Pottery fragment
Puerto Rico

When Christopher Columbus made human contact after crossing the Atlantic in 1492, it was the Taino people, the indigenous Caribbean people, that he first encountered, on Hispaniola. The encounter may have been the salvation – and subsequent enrichment – of Columbus, but it brought little but misery and disaster to the Tainos, a premonition of the wider genocide of the North American indigenous people that Columbus's discovery catalysed. Columbus enslaved some of the local people he encountered, killed others, handed over women to shipmates as slaves to be beaten and raped. He was to set up brutal forced labour systems for the mining of gold. Columbus's voyage brought with it, too, smallpox, yellow fever, bubonic plague, typhus, cholera, and other illnesses, to which the indigenous peoples had little or no resistance, and which soon decimated them. Within a couple of decades, nearly a quarter of a million people had died of these on Hispaniola, some 95% of the indigenous population. This linking of the Old World and New was to shape the history of both planet and people. But let us remember what and who was lost, in this exchange.

302 (1500 CE)
Inca pottery vessel
Peru

The Inca empire – the largest of the indigenous empires of South America, before the Spanish colonisers arrived – arose in the preceding time according to its own unique pattern, without the influence of other cultures. It illuminates, therefore, the range of possibilities by which a complex organised human society could be built in the time of the Holocene. It had sophisticated stone buildings, a far-flung network of roads, fine textiles, and a complex, hierarchical human organisation – but without the use of a wheel, pack animals, a system of writing, or iron. Nor did the Incas use money, but instead exchanged the goods they made, and the services they provided, between different sections of society and between rulers and ruled. This experiment – one that lasted half a millennium – came to an end as the European invaders, with steel armour, horses, gunpowder, and a full complement of deadly pathogens, destroyed it and established their own reign. The Incas had a different means of organising society, with its own particular mixture of benevolence and terrible cruelty, but it long maintained their society in difficult conditions. It provides another prism on human life, and on human possibilities.

303 (1650 CE)
Earthenware
Mali, Africa

Mali was once the centre of the largest of the empires of Africa. Two contrasting resources were at the heart of this dominance. The first was that metal that has long had few obvious uses other than decoration, but enormous value in human minds in signifying wealth: gold. Mali's gold, exported through trading posts such as Timbuktu, provided much of Europe's supply. The second was more practical: salt. Mali's position between the Saharan desert, where a dried lake beds yielded so much salt that the local people built houses with it, and the salt-starved rainforest equatorial regions, led to a lucrative trade. This was no local peculiarity, for salt was a commodity that, in Medieval times, had stellar status in Europe too, comparable to the influence of the oil industry in modern times; in Poland, for instance, who controlled the salt mines in effect bankrolled the whole country. Salt was the indispensable means to preserve food to survive through the non-growing season – and in the hot equatorial regions, the physiological need for salt is yet greater. Its dominance is hard to appreciate in modern times, when food is routinely canned and frozen – but reminds us how power springs from the fundamentals of life.

304 (17th century)
Bellarmine face mask, Bartmann stoneware, salt-glazed

It's a funny kind of jug – indeed, it's meant to have a touch of humour, with a relief image of a face with a beard around the neck of it, portraying the 'wild man' of myth and legend. Some of these jugs were used to transport serious toxins, such as mercury, while others were 'witch bottles' and filled with items that should not be mentioned in delicate company. But the Bartmann (which means 'bearded man') jugs of the 17th century became one of the tracers of the widening out and speeding up of trade routes throughout the world. They are one of the distinctive kinds of stoneware produced in Germany, especially in the Rhineland, and which subsequently turned up in archaeological sites and shipwrecks in places as far apart as Bermuda, North America, the North Sea, and Australia. This was among the beginnings of what later became known as globalisation.

305 (1758 CE)
Marine technosphere: cannon flintlock flint from *HMS Invincible* shipwreck
East Solent, UK

The expanding maritime trade routes of the 18th century needed protection, and this military muscle also showed technological development, and technology transfer too, albeit one of an involuntary kind. The roots of the globe-spanning technosphere lie somewhere amid developments of this kind. The *HMS Invincible* was originally a French warship, before being captured by British. Then, its manufacture, with 74 guns, was so influential that 60 years later, at the Battle of Trafalgar, three-quarters of the British fleet had a similar design. The *Invincible* may have been invincible in war, but it was sunk by the vagaries of sediment transport on a sea floor upon which vigorous tidal currents continually play. It collided with one of the ever-shifting sandbanks, and never came home to port; its remains, though, were to become a focus of deep interest from marine archaeologists more than two centuries later. Ironically, the flintlock that is now part of this artwork, and was one of those French innovations so admired and copied by the British shipbuilders, has the most ancient connections. It can take us back not only to the Stone Age, but also to the Cretaceous sea floor, above which swam ammonites and mosasaurs. That, now, really is time travelling.

306 (17-18th century)
Stuart Jacobean period clay pipe bowl
UK

Christopher Columbus was not the first European to see the New World (after the Vikings, that is): the sighting was made by one of his crew – but Columbus stole the credit anyway. He, though, apparently was the first European to see the smoking of tobacco, a habit that in North America stretched back thousands of years. Soon, of course, this habit, and the 'peaceful drunkenness' that it induced, spread to Europe, and then throughout the world. It did meet resistance: King James I famously condemned it as the 'blacke stinking fume … of the pit that is bottomelesse' and raised the tax on it forty-fold, though that did not dim tobacco's popularity among his subjects, or elsewhere. Tobacco has taken over in other realms, too. The plant, native to the Caribbean region, was spread across the world, as tobacco production flourished on every continent save Antarctica. The plant itself, *Nicotiana tabacum*, is robust and adaptable. It escaped from the plantations in many parts of the world, to become a globally distributed invasive species, a biological marker of this new worldwide trade network. The myriad clay pipes made for the consumption of this most remarkable weed, like this one here, stand for far more than a quiet smoke.

307 (1776 CE)
Soil from James Watt's shed, birthplace of the Industrial Revolution
Bo'ness, Scotland

A revolution started in James Watt's shed, in 1776, that was to allow things that we now call industry, technology and modernity to take over all of our lives – and to leave an increasingly indelible mark on the planet, too. It has a lot to do with energy: replacing the constant but limited and diffuse energy that humanity had long taken from the Sun, in one form or another, by the concentrated, enormous energy source extracted from the ground in the form of coal, and later oil, and gas. Coal had long been used by humans, since the time of the Romans and before – but there was a problem. Trying to mine large quantities of it meant digging deep into the ground to extract coal, beyond the surface coal outcrops. Any deep hole in the ground soon fills with water, and that soon stops any further digging and coal extraction. James Watt's invention, a steam engine, was able to power machines to effectively pump water out of the coal mines, and so coal could be taken from deeper and deeper underground. With the energy that extra coal gave, the steam engine could be adapted to all kinds of other uses, such as railways – which could carry coal to yet farther parts of the land. And so on… once started, this revolution could not be stopped. It is still going, though we do not know quite where to.

308 (1822 CE)
Chinese porcelain plate from the *Tek Sing* shipwreck
China

It has been called the *Titanic* of the East. The *Tek Sing* (or 'True Star') was a Chinese ship carrying passengers and porcelain from China, bound for what was then the port of Batavia in the Dutch East Indies, that we now know as Djakarta in Indonesia. Alas, the captain decided to take a shortcut through the narrow Gaspar Strait, that connects the South China Sea to the Java Sea. The *Tek Sin*g ran into a reef and sank. Ships passing a little later managed to rescue some 200 people – but some 1500 were drowned in the catastrophe. The remains of the *Tek Sing* were discovered a little over twenty years ago, and the cargo excavated. Some 350,000 pieces of Chinese porcelain were brought to the surface. It is a tragic story – but one which illuminates the growing scale of mass market manufacture, and its human and economic consequences, as the world moved into the industrial era. The growth in scale of manufacture and trade, was to continue, and lead to a change in not just the patterns of human history, but that of the planet too.

309 (1918 CE)
Pepto-Bismol, containing bismuth subsalicylate, a new man-made compound
Ohio, USA

Bismuth is a metal, related to arsenic, that once had the honour of being the largest atom (with an atomic weight of 209) recognised as stable. Alas! It was found to be very slightly unstable – though as its half-life is a billion times longer than the age of the universe, one need not worry about its level of radioactivity. One can find it in nature in quite a few ways: just by itself, as a native metal, in silvery crystals which can take on an iridescence when they tarnish; and as sulphides and sulphosalts, oxides, phosphates, arsenates, silicates and more besides – in all, 228 valid bismuth minerals are recognised, a respectable proportion of the ~5,200 minerals known on Earth. Pepto-Bismol, though, does not qualify for formal status as a mineral. It joins the hundreds of thousands of synthetic compounds that have, just in the last 70 years, made the Earth one of the most chemically diverse planets in the cosmos.

310 (1941 CE)
Holocaust: a brick from Terezin concentration camp fortifications
Czech Republic

In modern times, everything grew larger: trade, cities, communication networks. So too, did human atrocities, even in Germany, one of the most economically and culturally developed countries in Europe, with a fine tradition of the arts and sciences, philosophy, literature. This, it turned out, was no defence to the evil that took hold there before and during World War II, and the ease with which entire human communities could be targeted for a 'Final Solution'. Some six million Jews were murdered in the Holocaust, and millions more 'sub-humans': ethnic Poles, Roma, gay people, and others, by death squads, and then in the concentration camps. There is the scale of this genocide to contemplate (perhaps not unparalleled, even then, depending how the victims of Stalin's purges are counted). But what is striking was its organisation, with a bureaucratic exactitude and industrial efficiency, that normalised the process of eliminating human lives, not least for the many ordinary people who took part. The philosopher Hannah Arendt, in considering one of the chief bureaucrats involved, Adolf Eichmann, memorably called it the 'banality of evil'. Post-war German society has shown extraordinary moral courage in facing this history and trying to understand this evil, to help us all be on guard against it. For genocide did not start or, alas, stop with the Holocaust.

311 (1944 CE)
WW2: barbed wire strips from D-Day
Omaha beach, Normandy, France

War is hell, said General William Tecumseh Sherman, during the American Civil War. As the nineteenth gave way to the twentieth century, that hell burnt ever brighter and more fiercely – quite literally. Alfred Nobel's discovery of high explosives, that could be delivered by artillery shells, changed the face of war – and the face of the Earth, too. By the First World War, the constant bombardment by this new kind of weapon could remove several metres from the tops of hills along the front line: the churned landscape that resulted has been called 'bombturbated': akin to the bioturbated soil turned over by worms, but on a colossal and infinitely less life-giving scale. The bombturbated soils of Verdun, for instance, still contain most of the bones of the million soldiers who died in that battle: less than a third of the victims were ever found. These and other bombturbated soils still contain, too, many unexploded bombs, that continue to kill people today. This kind of murderous downpour continued, and intensified, in World War II, delivered by both artillery and aircraft. It swept through, for instance, the soldiers who struggled onto this Normandy beach on D-Day. That day did provide hard-won deliverance from one evil, but only one. The bombing, and the bombturbation, has continued since, and is still with us.

ANTHROPOCENE
1945-PRESENT

312 (1945 CE)
Trinitite, from the Trinity test, the first atomic bomb detonation
New Mexico, USA

At 21 seconds and 29 minutes after five in the morning in Mountain War Time, on July 16th 1945, at the Alamogordo military test site in the Jornada del Muerto ('Journey of the Dead Man') desert, New Mexico, the first atomic bomb was exploded. Its code name was the Trinity Test, and the bomb itself was called the Gadget. The Gadget was not only of an utterly new design, but included large amounts of plutonium: an element that could be said to be new to Earth, for it does not occur in any significant amounts in nature, and needed to be synthesised for the purpose in a nuclear reactor. It took huge investment and an enormous secret operation to create the Gadget. But would it work at all? Some of the scientists involved set up a betting pool, with the mooted possibilities ranging from nothing at all (a complete dud) to 18 kilotons (i.e. equivalent to 1800 tons of TNT). The detonation in fact released 25 kilotons. In a circle more than half a kilometre in diameter, the desert sand was flash-melted into a pale green, slightly radioactive glass that was given the name trinitite: a new-born and sinister cousin, one might say, of natural volcanic obsidian. After the test, one of the scientists involved, Robert Oppenheimer, recalled thinking of a line from the Bhagavad Gita, 'I am become death, the shatterer of worlds'. It was soon to be visited upon Hiroshima and Nagasaki.

313 (1947 CE)
Rubble from 'Devil's Mountain', Teufelsberg, created from the post-WWII debris
Berlin, Germany

When much of a city has been reduced to rubble in wartime, what should be done with the debris? There are a number of patterns to the strata that result. In post-WWII London, for instance, much of the debris from the more than 100,000 houses damaged or destroyed in the Blitz was taken to fill in marshland around the Lea Valley, as the foundations for future development. In Berlin, the yet greater amount of war-generated rubble was used to bury Albert Speer's Military College (it was too sturdily built to blow up) and build a more visible monument: the Teufelsberg ('Devil's Hill'): 70 metres high – the tallest hill in Berlin – and a kilometre long. In the Cold War times that followed, it became a US spy station, complete with radar domes, though now it has a gentler and less sinister use, as a kind of centre for alternative living. The colourful and irreverent murals on the walls of the former Cold War installation are alone worth the visit.

314 (1947 CE)
Chert, flint, quartz, galena, sphalerite, dolomite and chalocopyrite from 'America's most toxic ghost town'
Picher, Oklahoma, USA

Metals are such useful things for our modern civilisation, indispensable to many of our technological marvels. The mining of metals has gradually developed over thousands of years, and then, in the last century or so, zoomed dramatically in scale – in 1950, for instance, 2.4 million tons of copper were mined globally, while by 2015 it was 19 million tons – and in diversity. To the traditional copper, lead, zinc, tin and such, there can now be added a frenzied search for gallium, dysprosium, neodymium (and many more such) to help build our ever-more-ingenious gadgets. The Earth's surface, as a result, is becoming ever more enriched in these metals, just as our mining activities are energetically depleting lower layers in the crust in them. Picher in Oklahoma is one of the many towns that acted as a source for this metallic cornucopia: undermined, surrounded by toxic waste heaps, with contamination by lead in both groundwater and children, it was finally evacuated – compulsorily – to become a ghost town. Towns will grow elsewhere, but this monument, the roots of which run deep into the ground, will take millions of years to efface from our planet's geological archives.

315 (1950s CE)
Fertiliser: "Elixirs of Death"
UK

It is a chemical process that is said to keep nigh on half the world's population alive. Take nitrogen from the atmosphere – generally an unreactive gas – and combine it with hydrogen, and ammonia is produced, the basis for nitrogen fertilisers. Fritz Haber and Carl Bosch shared a Nobel Prize for this invention which, from the mid-twentieth century, saw a vertiginous rise in nitrogen fertiliser manufacture, and consequently in food production, and in turn in human population. That other major fertiliser, phosphorus, comes not from the air but from rock, including from the fossilised bones and excreta ('coprolites') of dinosaurs. There is now somewhere between two and three times more reactive nitrogen and phosphorus at the Earth's surface than before this giant planetary fertilisation experiment started. It gives life in one sense, but takes it away in the other, for these fertilisers are washed from the farmers' fields into rivers, and then into the sea. There, they stimulate massive plankton blooms in places like the Baltic Sea and Gulf of Mexico, and these, on drifting to the sea floor, decay and use up the oxygen, to suffocate bottom-living animals across, now, something like 250,000 square kilometres each year. 'Dead zones', these are called. They are another symptom of our emerging Anthropocene world.

316 (1950s CE)
Chicken bone: the planet of the chickens
Hull, UK

In the Anthropocene, what has become the utterly ordinary can at the same time be astonishing, unprecedented. A chicken sandwich, now, is an everyday purchase pretty much anywhere in the world where people live. The animal that enables this is the modern broiler chicken. It is a descendent of Asia's red jungle fowl, a fast-running bird with bright plumage, which has been domesticated for thousands of years, for eggs and meat, and for cockfighting too, always, though, being much the same kind of bird through this history. Then came the Chicken-of-Tomorrow contest in the post-WWII USA, that sparked an intense breeding programme. A decade or so later, a monster had been created: approaching twice the height of its pre-war ancestor and four times its weight, this giant meat-heavy bird is now forced to grow to its full size in some six weeks before its mechanised killing (its stressed frame would not survive for much longer, in any case). The broiler chicken is now, by more than an order of magnitude, the world's commonest bird, at more than 20 billion being alive at any one time, outweighing, by some three times, all of the rest of the world's birds put together. As a result, the mortal remains of this technological, though still sentient, creation can now be found in every supermarket near you. In the far future, its fossilised remains will be one of the marker fossils of this new, human-driven, epoch.

317 (1950s CE)
Piece of *Cutty Sark*, Old Nannie
London, UK

Here, now, we cross time and epochs quite freely, and maybe glimpse a path back into the future. This piece of Nannie Dee, the scandalous – and murderously inclined – witch of Robert Burns' poem *Tam O'Shanter* that is the figurehead of the *Cutty Sark*, was carved in the 1950s, from a piece of Canada pine. It replaced the 1869 original, when this charismatic sailing ship was commissioned to carry tea from China. For all of her grace, she was soon outpaced by the ever-more-powerful steamships that proliferated across the oceans, and went from being a working ship to become a national symbol of past sailing glories. The *Cutty Sark* was, thus, left behind in the rush for globalisation. But as the downside of this mechanised craze for speed becomes clear – the shipping industry now emits nearing a billion tons of carbon dioxide each year – could it become a reminder that the wind might be called upon to carry our wares once more, in its quiet and beautiful way?

318 (1954 CE)
Rivers and megacities: sea-excavated formerly buried objects from Thames estuary landfill
Tilbury, UK

Out of sight, out of mind – and soon, somehow, gone. That is our usual thought, such as it is, whenever we consider what goes into our wheelie bins, and then on into our landfill sites: our trash is safely buried, and surely will stay there. This is not always the case, though, and will likely get increasingly less so. Our cast-offs are beginning to re-emerge from their brief underground sleep, to join us again. Many landfills have been sited close to sea-level, taking the space formerly occupied by gravel strata: ancient river and beach sediment which now lines our driveways, or has become a prime ingredient of our endless concrete constructions. As climate warms, and sea level inches upwards (some 20 centimetres in the last century, though now speeded up to approach half a centimetre a year), the waves have begun to bite higher up the shoreline, and extend the cliff lines a little further inland. Here and there, they have begun to exhume old landfill sites, as at Tilbury, a tiny fraction of which is now reburied in this layer. The landfill material – bottles, bricks, cans, half-decayed food waste and all – is now re-entering the sedimentary cycle, to be washed along the shoreline, and also to impact on living organisms, human and non-human, as plastics and toxins are able to become biologically active again. A new and disquieting kind of geology is being born along the world's evolving shorelines.

319 (1958 CE)
The dawn of the nuclear age: a coconut shell from Bikini Atoll
Marshall Islands, USA

The hydrogen bomb sent signals around the world. One signal was that humans had invented a deadly new weapon, exploiting forces otherwise only found in the core of our Sun, so as to better threaten tribal rivals on other continents. Another signal is an unintended consequence of this show of strength, one that might become global marker for a new geological epoch. H-bombs are so powerful that, when exploded at the Earth's surface, they send radioactive debris up into the stratosphere, where it can circle the whole Earth before eventually drifting down to the ground. So, unlike the earlier, less powerful atomic bombs, where the radioactive dust mostly fell in the region surrounding the blast, here the signal (of radionuclides such as plutonium, caesium, americium and radiocarbon) is planet-wide. It is not *quite* synchronous (the quality most keenly sought for in a geological time boundary): the radioactive particles fell onto the southern hemisphere a few months later than in the north, and they reached the deep sea floor a little later than they reached the land surface. Nevertheless, the entire Earth's surface (us included) was, very nearly in the same instant of planetary time, made radioactive. It might become the formal marker for the onset of the Anthropocene.

320 (1962 CE)
Porridge Oats containing highly hazardous pesticides
UK

It is an invisible sign of modern times. There is little more innocuous – or avowedly healthy – than porridge oats, and yet these too can contain detectable amounts of pesticides. This means of maintaining the crop monocultures, that today produce most of our food, is a modern invention, and a surprisingly far-reaching one. Lochnagar, for instance, is one of Scotland's most remote mountain lakes, set among wild moorland; with no rivers flowing into it, it is entirely rain-fed. And yet, a core of mud deposits taken from the lake floor, carefully analysed, has shown, in layers that represent the mid 20th century onwards, measurable amounts of DDT, dieldrin, aldrin and a host of other pesticide residues, which entered it with the rain. This wide-flung escape of persistent organic pollutants, likely drifting across landscapes as fine aerosols, is one reason why populations of insects (and not just the ones we regard as pests) have plummeted worldwide in recent decades. The state of the nation's porridge is just one symptom, among many, of the agrochemical warfare waged in our fields.

321 (ca 1970 CE)
Wroewolfeite: a synthetic substance that may never have existed before in the Universe
Devon Friendship mine, Mary Tavy, Devon, UK

The range of minerals of the Earth's crust used to be thought to be a stable component of our planet, over its four-and-a-half-billion-year history. Then, a visionary analysis of Earth's minerals by the mineralogist Robert Hazen and his colleagues revealed that they in fact showed an evolutionary pattern, from a few hundred in meteorites, to a couple of thousand on an early Earth before life appeared, to about five thousand on a living Earth with photosynthesis (to produce many oxide and hydroxide minerals). This has generally been the complement for the last couple of billion years – until, that is, humans appeared, and began to stretch mineral chemistry further. The process started thousands of years ago, as ores were smelted to produce pure metals (rarities in nature) and alloys. Then, over the last century, another great leap in 'mineral' numbers began (synthetic minerals are no longer regarded as true minerals by mineralogists); some new combinations have been made in the course of mining, like this wroewolfite now giving its distinctive imprint to this urn. Many others have been formed in the busy laboratories of the materials scientists – graphene, synthetic garnets for lasers, and many more. Very many more. A database cataloguing these novelties now lists more than 200,000 new synthetic inorganic crystalline compounds (minerals, that is, in all but formal classification). While biological diversity plummets, mineral diversity is climbing to levels perhaps seen nowhere else in the cosmos.

322 (ca 1970 CE)
Coral from threatened reefs
Indonesia

Just as canaries in a coal mine give early warning signals of danger in the mine air, so coral reefs – hyper-diverse but delicate biological oases – are sentinels for the wider biosphere, on which we all depend. The carbon dioxide from those coal mines, and oil and gas wells and felled forests also, has now put about a trillion tons of carbon dioxide into the atmosphere (equivalent to a layer of human-produced gas about a metre thick, now growing at the rate of a millimetre every fortnight). The heating effect from the resulting greenhouse warming – greater by far than the energy we directly use from burning these fossil fuels – is mostly going into the oceans, being now roughly the equivalent of pouring a few billion cups of hot tea into the oceans, every second. The warming oceans are bad news for corals, especially during what have recently become known as 'marine heat waves', when the coral organisms 'bleach', often fatally, by losing the single-celled photosynthetic algae they cohabit with – or simply die through overheating. The growing threat to coral reefs is not the first of this kind they have faced: they effectively disappeared 55 million years ago, for instance, during an ancient (and entirely natural) global warming event. Reefs at that time did return. But, the recovery took several million years.

323 (1976 CE)
Material remnants from Gbene-ol, an oil spill site in the Niger Delta
Kegbara Dere town, Gokana LGA, Rivers State, Nigeria

Oil is such a convenient energy source: very energy-dense, easy to transport and to modify into different kinds of fuel for different purposes (and into other materials such as plastics, too). The location and extraction of oil involves extraordinary feats of engineering, for its underground reservoirs are complex (resulting from a kind of three-dimensional superposition of many ancient landscapes, or 'submarinescapes'). Dangerous surprises abound, not least when high-pressure gas pockets are struck (in the early days of oil drilling, these could sometimes propel the entire drill string into the air, like so much gigantic metallic spaghetti). The expertise and the technology around this enormous global business are more refined these days – but oil spills still occur all too frequently, with effects that catastrophically impact local communities and ecosystems, as in this sample, from the heavily-exploited Niger Delta, one of the most polluted places on Earth. It can take decades for affected areas to recover. And the invisible effects of the whole business – the heating of Earth's climate – will take many millennia to fade away.

324 (1979 CE)
Acid rain: a sample of peat and pine needles from under a Sitka spruce forest in an acidified catchment in Galloway
Scotland

Acid rain, arising from the burning of sulphur-rich coal and oil to produce rainfall of dilute sulphurous acid, was one of the great environmental problems in the mid- to late twentieth century. Its effects were starkly visible, as healthy forests turned to graveyards of whitened tree skeletons. It is also among the global environmental problems that have been – more or less – successfully managed. Passing the flue gases from the power stations through a suspension of finely powdered limestone absorbs nearly all the sulphur. Many of the forests have grown back as this kind of technology was widely adopted. There is one cloud, though, behind this silver lining. The filthy, polluted, acid-containing air of the mid-twentieth century also produced clouds that reflected some of the Sun's heat – and so helped slow down global warming, as greenhouse gas levels began to rise in the atmosphere. As the air became cleaner, so the warming of the climate sped up in the late twentieth century.

325 (1979 CE)
Deep ocean manganese polymetallic nodule from Glomar Explorer
North East Pacific Ocean

The abyssal ocean floors, far from land and four kilometres or more below the surface of the sea, have long been mysterious places. They used to be thought to be completely dead ('azoic'), being cold, dark and at crushing pressures. They turned out, in fact, to harbour a great diversity of life adapted to those conditions and feeding on a 'long snowfall' (the beautiful words of that pioneering environmentalist, Rachel Carson) of organic detritus falling from the sunlit waters high above. So far from land, though, very little sediment accumulates on those ocean floors and, in those conditions, some peculiar kinds of chemical/mineral growth were discovered, once scientists – a little nervously – reached them in their bathscaphes. These are iron-manganese nodules, looking a little like fields of potatoes lying on those sea floors, and which grow *exceedingly* slowly (a millimetre or less per millennium) as these elements precipitate onto them from the seawater. The nodules can contain more than iron and manganese: their chemistry can include, too, nickel, copper, cobalt and a range of rare-earth elements – all now highly in demand, not least for the technology involved in the growth of clean, renewable energy. Alas, the energy may be clean, but plans to hoover up these nodules from the ocean floor, on an industrial scale, have consequences that are anything but clean, for the delicate deep-sea ecosystems. A legal and environmental battleground is now taking shape.

326 (1985 CE)
Coal from mountaintop removal mining
Appalachian Mountains, West Virginia, USA

Coal, far from being a dinosaur of the Industrial Revolution, is still alive and kicking, and raising hell in the battle between the energy barons of industry and the climate change warriors. There is simply so much of it, a legacy of times in Earth's past where mighty forests grew over many generations, to be buried and converted into seams that may be tens – and sometimes hundreds – of metres thick. There is enough coal easily available to power a few generations of global humans yet – and, at the same time, to definitively and irreversibly (for many tens of thousands of years, at least) derail the generally stable climate we have enjoyed for more than ten millennia, and take us with brutal speed into the world that the dinosaurs lived in, a much hotter world with little or no ice and much of the continents submerged. There is a cost right now in obtaining coal of course, as it is underground. But if it is not too far underground, one can simply expend energy from oil, to power gigantic excavating machinery, to decapitate whole mountains to get at the coal within them. It is an awesome process. It is also leading to awesome consequences.

327 (1988 CE)
Fly-ash from coal-fired power plants
UK

It is a quite distinct kind of geological signal, with few precedents in Earth's history (one of which was in the meteorite-generated conflagration in which the dinosaurs, and much else, became extinct 66 million years ago). But right now it is proving to be one of the most striking and durable signals of the Anthropocene. Burn coal or oil at high temperatures, and a kind of smoke will result – the kind that comes out of a factory chimney or a power station. Now look closely at these smoke particles that fall on the ground, a job best done with a scanning electron microscope. They have a distinctively spherical shape, with a micro-cratered surface from the escaping gases. Being made of carbon which has escaped complete combustion, they are pretty much indigestible, even to the hungriest microbe. Once they land in a peat bog, or a lake bed, or the sea floor, they may stay there, buried in that stratum, for many millions of years. They are termed spherical carbonaceous particles, or SCPs, by those who study them. In some parts of the world, where the Industrial Revolution started, they begin to turn up in the sediment layers dating back to the nineteenth century. For most of the world, the SCPs appeared in force in the mid-20th century, as fossil-fuel-based industry became global. The whole world, then, became smoked – and that smoke signal will last forever, as the strata that enclose them are buried and become the latest part of Earth's geological record.

328 (1989 CE)
Fragment of the Berlin Wall, found between the Brandenburg Gate and Checkpoint Charlie
Berlin

When different human tribes mark out their territories, much effort can go into constructing the boundaries, whether to keep the inhabitants in or the invaders out (or both). The Berlin Wall is one notorious recent example, its last iteration weighing in at something like a third of a million tons of concrete for the wall itself, though that does not count the mass of the electrified fence, the 'death strip' of sand, the armed guard posts and so on. (Even with these it is still less than one percent of the mass of the Great Wall of China, some two millennia older, and which shows how deep lie the roots of humanity's territorial reflexes). Today, there is almost nothing left of the Berlin Wall: the few tiny segments that still stand are tourist attractions, and reminders of a lost, if not widely lamented, world. Other segments have undertaken migrations, to museums and display sites across the world: Portugal, the Philippines, Canada, the USA (quite a few), London, South Korea. Smaller pieces are still sold in gift shops, and doubtless then go on to form an even more far-flung diaspora. It is a very small, very particular part of the new form of transport of mineral matter across the globe: no longer by wind or water or gravity, but by the quirks of human intent.

329 (1991 CE)
Nanotechnology: a dusting of Buckminsterfullerene, C60 nanotubes
Karelia, Russia

When it comes to the extraordinary kinds of molecular architecture that the humble carbon atom can indulge in, then nature and artifice are sometimes closely, almost inseparably, intertwined. The iconic cage-like structure of buckminsterfullerene, with its exactly 60 carbon atoms (and named after the geodesic dome designed by Buckminster Fuller) was first synthesised in the laboratory. It was realised that there are a number of other types of 'fullerene' with different numbers of carbon atoms, some spherical, some tubular, and that they occur in nature too, from meteorite impact sites and forest fires to the clouds surrounding distant galaxies. The manipulation of atoms in the laboratory – so that they can lead to the next generation of space age technology – now goes hand in hand with their detection in various corners of this planet, and beyond.

330 (1994 CE)
Wollemi pine: a tree thought to be extinct for 2 million years, now rediscovered
Kew Gardens, UK

One facet of scientific exploration is the finding of relics of bygone ages, that eke out an existence in some neglected spot of the Earth. Most famously, there has been the coelacanth, last seen in the fossil record in Cretaceous times, more than 66 million years ago, and then being discovered in 1938, in the deep sea off the African coast. The Wollemi pine is not quite so celebrated, but it made a bit of a splash too in 1995 after it was discovered in a remote canyon in the Wollemi National Park in New South Wales. It is not a pine but a kind of araucarian tree, of the kind that thrived in the time of the dinosaurs, and was thought to have died out a couple of million years ago. The original relic stand of pines remains threatened, from Australia's intensifying forest fires and from imported disease. But *Wollemia nobilis* has been cloned, and examples have been given as presents to visiting dignitaries, winding up in botanic gardens in different parts of the world, including to the Kew Gardens, from which this twig has been gifted.

331 (1996 CE)
Grass from Dolly the sheep's paddock
Roslin, Scotland

Dolly the sheep was named after Dolly Parton the singer, and also achieved rock star status as the first mammal to be cloned, in 1996 (she was not quite the first animal to be cloned: this was an African clawed frog, name unknown, way back in 1958). Nevertheless, it was quite a step in the ingenious human manipulation of life: the result of the nucleus of a mature sheep cell that was then carefully inserted into an unfertilised egg cell that had had its nucleus removed. This combination grew up into Dolly the sheep (who then went on to have several baby sheep of her own, in traditional fashion). The success of Dolly led to quite a few other things: the cloning of other animals, the development of stem-cell research (that is, developing the ability to turn one kind of cell into any other kind of cell), and yet other forms of re-engineering of the building blocks of life. This new kind of evolution of life on Earth is proceeding very quickly, in some direction as yet unknown.

332 (1996 CE)
Space junk: debris from the exploded spacecraft Cluster
European Space Agency

On 4th June 1996, there took place the maiden flight of a new model, the Ariane 5, the latest version of France's highly successful rocket series. It was carrying four sophisticated 'Cluster' satellites, meant to go into orbit to systematically measure the Earth's magnetosphere. Everything was 'nominal', perfect, for the first 37 seconds; then, a computer glitch caused the inertial guidance system to go awry, the rocket veered, broke up in a fireball four kilometres above ground, and scattered debris over some 12 square kilometres of French Guiana's savannah and mangrove swamp terrain. It was a catastrophic accident – but one quickly learnt from. It does not have the long-term consequences of the many thousands of pieces of space debris now quietly and almost invisibly piling up in orbit, which will only slowly (and some never) come down to Earth. That orbital trash layer, now, does threaten the dreams of humans to become a spacefaring species.

333 (2001 CE)
A bone from an animal that had stepped on a landmine and died
Angola

Landmines are one of the most evil expressions of humanity's seemingly endless capacity for war, and the ingenuity with which they have been devised gives one pause for thought about the human condition. Even after hostilities have ended, they are difficult and dangerous to clear, and abandoned minefields still kill thousands of civilians each year, mostly children, and (of course) animals too. Minefields show up deep ironies in the wider human enterprise. The demilitarised zone between North and South Korea, for instance, has been sown with many thousands of landmines. With human settlement and farming impossible, it has become a haven for wildlife, for which the landmines are a lesser risk than the dangers of modern agriculture and urban settlement.

334 (2010 CE)
Mycoplasma mycoides JCVI-syn1.0: the genetic material that programs an organism
USA

It is one of the many ironies of the Anthropocene that while the biosphere is rapidly degrading and losing diversity, human scientific ingenuity has begun synthesising living organisms. This layer contains the mortal remains of some 21 million cells of the bacterium JCV1-syn1.0: the first kind of cell in Earth's long history to have, as parent, not another bacterium but a computer and attendant scientific team in J. Craig Venter's laboratory in California. Its DNA, comprising 1,078,809 'base pairs' of the component chemicals – cytosine, guanine, adenosine and thymine – was synthesised in the laboratory, and then allowed to commandeer a bacterium, programming it from then on. JCV1-syn 1.0 is relatively simple, as bacteria go. The race is on, now, to use this knowledge to create larger and more complex synthetic organisms. The science is moving very quickly.

335 (2003 CE)
War-torn countries: army stopwatch used to time bombings in the Iraq War
UK

In the Anthropocene, conflict between human societies shows little sign of lessening, and may be symbolised by this deceptively innocent-looking piece of military equipment. As this epoch unfolds, though, another factor is coming into play. In the Holocene, conflict took place on a planet that was generally stable, and on which the geometry of land and sea stayed much the same, no matter how the power games between nations panned out. In the Anthropocene, as climate warms, ice melts, and sea level rises, the pattern of the land is set to change as it becomes progressively inundated by the sea. We now have a Pliocene-like atmosphere, and so a Pliocene-like sea level, some 10 to 20 metres above the present one, is likely to follow. Therefore, any national boundaries, and marine exclusive economic zones, that are tied to current sea level, will have to adapt to this change – an enormous challenge not currently covered by the latest iteration of the International Law of the Sea, which was designed for Holocene stability. The idea is now growing that this complex but fundamental legal framework should be adapted for the more unstable Anthropocene conditions that are emerging, to help try to keep the peace.

336 (2004 CE)
Rock from Onkalo, where nuclear waste will be buried for 100,000 years
Olkiluoto island, Finland

It is rare that human institutions plan very far into the future, into the long future time that is the mirror-image of deep geological time. There have been exceptions, of course, and the disposal of nuclear waste is one where the long view – a *geologically* long view – is integral to the planning. This reflects both the long half-lives of some of the radioactive elements in the waste, such as plutonium, measured in tens of thousands of years, and the specific kind of fear widely triggered by the thought of nuclear waste: of silent, invisible, relentless danger. Hence the seeking of sites, at great expense, to store radioactive waste, deep underground, beyond the reach of even a resurgence of future glaciers, and within rocks whose properties can be measured, controlled, predicted. Other environmental concerns deserve a similar long view, among them global warming, plastics pollution, and biodiversity loss.

337 (2005 CE)
Mined materials from Bayan Obo, largest deposits of rare earth elements yet found
Bayan Obo Mining District, Inner Mongolia

Rare-earth elements are a little paradoxical. They are not particularly rare, as elements go, neither are they particularly earthy, being soft silvery metals when pure. But they are quite widely and thinly scattered in most rocks, and so concentrated ore deposits *are* rare. There are quite a lot of the rare earth elements – some 17 in total – often with unwieldy names like neodymium and dysprosium and gadolinium. Before we became a technological species, we had no use for them – they seem not to serve any particular biological function. But now we have built a planet-spanning technosphere (or perhaps, more precisely, we have been caught up in its scarily rapid evolution) these strange metals have become vital to many of our newly emerged gadgets, such as mobile phones and wind turbines. Mines that produce rare earth elements are therefore highly prized and jealously guarded, even though the process of extracting them is dirty and costly. As the Anthropocene unfolds, places like Bayan Obo, the largest deposit of these elements in the world, will be key nodes in the complex power structures of our present and future times.

338 (2006 CE)
Bee pollen, colony collapse disorder
Northern Spain

As human influence has spread across the planet, the decline, or demise, of species of lemur, say, or of orchid, or rhinoceros, is a consequence of our growing impacts. But for long it seemed that the world of insects – so small, so common, so omnipresent – would always be able to thrive, no matter what. Then a few decades ago came hints that not all was well in this realm too. There seemed to be fewer splattered bugs on car windscreens. Insect-eating birds seemed to be doing less well. Then, a few years ago, the numbers came in. A patient, meticulous study on a German nature reserve showed that the mass of flying insects there had decreased, in less than 30 years, by three-quarters. With other studies showing similar results, there came the shocking realisation that what was soon called an 'insect Armageddon' was in train, over much of the world. What was causing it? There are a host of smoking guns: artificial lights, habitat loss, pesticides. One expression of this insect decline is the increasingly reported 'colony collapse disorder' in honeybees, where most worker bees suddenly abandon the hive. As with the wider syndrome, there may be multiple causes, though neonicotinoid insecticides and parasites are commonly suspected. Clearly, all is not well with the biosphere, at a fundamental level.

339 (2009 CE)
Conflict minerals
Congo

Significant amounts of the minerals that enable our burgeoning technology – smartphones, computers, wind turbines – to function come from parts of the world where conflict is rife, and where the profits fuel further conflict, violence, and exploitation of local people. A longstanding example has been the eastern Congo, rich in metals such as tantalum, tin, and tungsten. In the complex production and supply chain, often starting with artisanal miners, many of the profits have ultimately found their way to local warlords, and thus to fuel further instability in the region. It is a growing problem of the Anthropocene, and is not the only example – the mining of amber, and its exquisite, lucrative fossils in Myanmar (Burma) is another. Slowly, fitfully, legislation is being put into place to address this problem, aimed at compelling traders to check and monitor supply chains. Will it work? – only time will tell.

340 (2012 CE)
Part of a ship from Chittagong ship breaking yard, 'where ships go to die'
Bangladesh

How many moral dilemmas can you pack together around one object? A ship at the end of its life contains a great number. It is mostly made up of many thousands of tons of steel, and for half a century or more most of the world's ships have simply been deliberately run aground into the beaches of Bangladesh and India. These are the improvised breakers yards in places like Chittagong (once the biggest such in the world, and still the most notorious). It is a very effective form of recycling – one might say a 'green industry' – but very costly in human terms. The ships are broken up in the most low-tech way, by many thousand workers (including many children), earning a few dollars a day, with no safety equipment and no financial security; unsurprisingly, there were hundreds of accidental deaths each year. It is yet one more thorny issue to be worked through – where the obvious dangers are pitted against resources and employment prospects for a developing country – to add to all the others brought in by this new epoch.

341 (2013 CE)
Regurgitated plastic from a baby albatross
Bird Island, sub-Antarctica

When plastics were invented, they promised a bright, clean, safe new world. They are light, strong, colourful, cheap, decay-proof, and almost infinitely mouldable into a cornucopia of useful shapes. The plastic world was duly built. Between 1950 and today, plastics production ramped up from about a million tons a year to more than 350 million tons a year: on average, that's now our own weight in plastic each year. Plastic is now quite indispensable to the safe, comfortable, pleasurable lives that many of us lead, and so cheap that much of it is thrown away after just one use. A small fraction of our collective plastic waste – currently several million tons each year – is washed into the sea. Much of it is less dense than seawater, and so either ends up floating in ocean gyres like 'The Great Pacific Garbage Patch', a thousand kilometres across, or is washed up on beaches: like driftwood, but with much greater durability. Seabirds starving to death, because their stomachs are packed with plastic, are one of the most obviously distressing consequences.

342 (2016 CE)
Plastiglomerate: bonded grey sandstone pebble mix with mica, Polypropylene, green rope, HDPE, red fish box and blue creel hook aggregate
Shetland, Scotland

Light a bonfire on a beach these days, and one can make a new kind of rock: plastiglomerate, the modern version of that ancient rock, a conglomerate. Any plastic around the fire melts, and binds the sand and pebbles together, enclosing as technofossils any not-fully-melted plastic objects, such as rope, fish boxes and creel hooks. It is a minor but distinctive part of the global plastics phenomenon that has so quickly overtaken us. It is also one that gives a greater chance of finding a route into future geology. The plastic, being weighted down by the pebbles and sand it binds together, will more quickly settle to the bottom of a sea floor or a beach, and be covered by more layers of sediment. If that trajectory continues, the plastiglomerate fragments will begin the trajectory towards burial within thick accumulations of strata. If brought back to the surface millions of years later, it will be as curious, carbonised and (by then) harmless impressions on a rock surface, perhaps for some far future palaeontologist to puzzle over.

343 (2017 CE)
Jellyfish crisps: marine dead zones and jellyfish blooms
Denmark

The Myxocene, the fisheries biologist Daniel Pauly has called it: an oceanic realm of jellyfish and slime, is the state towards which our oceans are heading. It is one more part-synonym for the Anthropocene, and an unusually telling one. A central feature is oxygen starvation, which is happening in two ways: in particular coastal regions where agricultural fertiliser runs into the sea to stimulate plankton blooms, which decay to form stagnant 'dead zones'; and, simply, globally, by warming the ocean waters, which means they can hold a little less oxygen. The organisms that can tolerate low oxygen conditions, such as some kinds of microbes – the slime – and jellyfish, will thrive. Most of the rest of oceanic life: fish, crustaceans, corals, and the humans who have dependence on them, will suffer. There are many precedents in the geological record for Myxocene-style oceans. They are mostly associated with greenhouse worlds. Ironically, the strata they often produce – the 'black shales' that are the relics of the many 'dead zones' of the deep geological past – are now those sought by geologists as the source rocks for many oilfields. History often repeats itself. Earth history, too – and jellyfish crisps are at least one way to make some use of an unwanted revolution.

344 (2018 CE)
Microplastic from the Earth's deepest ocean, the Mariana trench
Western Pacific Ocean

One might have thought that the deepest ocean trench in the world, 12 kilometres below the sea surface, with the nearest islands being mostly uninhabited, would be one of the few pristine environments left in the world. In fact, this true abyss is a trap for our debris, and not a haven from it. It contains levels of persistent organic pollutants higher than in some industrialised estuaries. And, like nearly all areas of the ocean floor now, it is being dusted with microplastic particles, such as polyester fibres washed out of our (now mostly plastics-based) clothing. These are so light that they can drift thousands of miles in the ocean currents before settling. Even thousands of miles from land, deep ocean muds typically now have several thousand plastic fibres on each square metre of sea floor.

345 (2018 CE)
Monarch butterflies and milkweed seeds
USA

The wings of a Monarch Butterfly are pressed into almost unbelievable work, taking them on annual migrations of thousands of miles between as far as Canada, to California or Mexico, and back. But the milkweed on which the larvae feed is often displaced by farming, and climate change is beginning to dislocate their complex and dangerous travels. The Monarch has lived through the repeated climate changes of Pleistocene times, but these were within the almost metronomic limits of warm and cold of the Ice Ages; life, including the Monarch, simply adapted to these repeated climate oscillations. The current global warming is now taking us out of that climate envelope into unknown (for millions of years) and hotter territory. The Monarch is one of countless species that are being edged towards extinction by the unprecedented pressures of the Anthropocene. How it will fare will be an indicator for the rest of life.

346 (2019 CE)
Stones from the first glacier to disappear in Iceland
Okjökull

Okjökull glacier was officially pronounced dead in 2014, the first of Iceland's named glaciers to succumb to global warming. It hadn't quite disappeared – there was still a small pile of dead ice – but it no longer had the mass to be able to flow, and so its metabolism had ceased. A small plaque was put up five years later, noting the date and the concentration of carbon dioxide in the air – 415 parts per million. Glaciers, one might say, wax and wane. How significant is Okjökull? One might glance across the Arctic regions to Baffin Island. The receding edge of the ice cap there is exposing the remains of mosses, crushed and frozen from the last time the area had been over-run by ice. Carbon-dating showed that this was 40,000 years ago, and so that area must have been continuously ice-covered since then. It is a measure of the scale of heating in this, Anthropocene, time. The heat continues to build, especially in polar regions, for the melting of highly reflective ice and its replacement by heat-absorbing dark land and water is amplifying the process. Okjökull is only the first to go.

347 (2020 CE)
Ocean acidification: coral
Guadeloupe, France

There are some processes on Earth that are, for now, holding back global warming. One is that part of the carbon dioxide we are emitting is being absorbed into the ocean waters, rather than staying in the atmosphere to help ratchet up the greenhouse effect. So far, so good, but there is a downside, and one so considerable that when its scale was realised at the beginning of this millennium, it was quickly tagged as 'the other carbon dioxide problem'. Dissolved in the water, the carbon dioxide is causing ocean acidification. Already, the acidity of the surface ocean waters has changed by about a tenth of a pH unit: this does not sound much, but as the pH scale is a logarithmic one, this means about 30% more hydrogen ions in the water – enough already to impact upon marine life. Those most vulnerable are animals which build their skeletons of the mineral aragonite, a form of calcium carbonate. Aragonite is harder than its better-known cousin, calcite, but is more prone to being dissolved. And so, such animals which use it, including the beautiful sea butterflies in the plankton, and the corals, are already beginning to suffer from the equivalent of thinner and weaker bones.

348 (2020 CE)
3D printed coral
California, USA

The impending loss of most or all of the world's coral reefs, as temperatures rise inexorably above the physiological limits of the corals that build them, has led to a proliferation of ideas to repair at least some of the damage. The 3D printing of artificial coral skeletons is one – making these out of concrete, or clay, or calcium carbonate, or even out of a kind of cellulose-based polymer to mimic the light-scattering properties of real coral skeletons. Humans here are trying to mimic nature. These synthetic skeletons are placed in damaged reef areas, and then coral larvae are grafted on to them, to increase their (usually small) chances of survival and to speed up the process of forming a new part of the reef structure. These experiments – that allow different shapes, and arrangements within the reef to be tried out – so far seem to help in restoration efforts. It is, at least, buying a little time for some reefs. The only long-term solution, of course, is to turn down the heat, and the levels of ocean acidity.

349 (2020 CE)
Microplastic from tyres
UK

The predicament of global plastic solution, which has been creeping upon us for the last 70 years, has exploded into a full-scale crisis in the last decade. For some forms of plastic, monitoring where it travels to is relatively straightforward, even for microplastics that can only be seen with the help of a microscope. Thus, the fibres that wash off our clothes in their billions have distinct shapes, and are often brightly coloured: once extracted from sea water, or a sediment sample, or the guts of a fish, it is hard to mistake them for anything else. But other microplastics are trickier to spot. Tyre wear, for example, is the second-largest microplastic pollutant in our ocean after single-use plastic. Vehicle tyres partly made of synthetic rubber, are thought to release at least 60,000 tons of microplastic particles – just in the UK – as they wear down, for these to be washed from roads into rivers and then into the sea. These dark irregular particles are not so easy to recognise, though, and need chemical analysis as well as a trained eye, to try to work out where they are going, and what effect they are having on living organisms.

350 (2020 CE)
Soot and cryoconite material drilled from ice cores in 'Greenland's Dark Zone'
Greenland

The world's great icecaps are like bright, gigantic mirrors that reflect most of the Sun's rays that shine on them, and so help keep the planet cool – and thus help maintain the conditions for their own existence. Therefore, if those mirrors become dusty, that has consequences for both ice and planet. There is always wind-blown dust, of course, especially in cold, arid, glaciated landscapes, and this forms a very particular pattern on the ice mirror. The extra warmth from heat absorption in summer causes meltwater to collect in small depressions, which then deepen to tiny pothole-like ponds – called cryoconite holes. Dotted across the ice surface, these can form little natural aquaria, harbouring microbes, algae and tiny animals such as rotifers. Within this arctic landscape, they can look a little surreal. Modern cryoconite holes are now more super-charged than they used to be, as the dust settling on Greenland now includes far-travelled, highly heat-absorbing soot generated by factories in the northern hemisphere. It is one more factor controlling the balance of Greenland's ice, which is currently shrinking, by something like a million tons a minute.

351 (2020 CE)
Ash from wildfire, from a home burnt to the ground
New South Wales, Australia

Climate change cannot come closer to home than when it burns your house down. The terrifying scenes from Australia in 2020, when more than 70,000 square miles were burnt, and from the western USA and Canada in 2021, made an eerie and unsettling impression. And yet, the significance and meaning of fires such as these is not straightforward. Forest fires have been part of the Earth System since life moved on to land, in the Devonian Period some 400 million years ago, and conflagrations were frequent in the Coal Measures forests. Some forest ecologies, indeed, are dependent on forest fires, for instance to enable the germination of some kinds of seed. While the fires are dramatic and powerful, the links with anthropogenic climate change – real enough, for altered regional temperature and rainfall patterns, and fire incidence will be altered too – are complex. There are some simple patterns in the Anthropocene, but this is not one of them.

352 (2020 CE)
Silicon, one of the most important technological materials in the 21st century
Italy

It still seems extraordinary to a geologist that silicon should be the basis of our ultra-high-speed modernity. Silicon! It is the basis of most rocks on the planet, of quartz, of feldspar, of mica, of granites and basalts and sandstones. But these are *rocks*, the very stuff of the Stone Age, and linking these with quicksilver calculations was for long a bizarre proposition. In the 1950s, Isaac Asimov wrote a short science-fiction story some decades ago, featuring some imaginary silicon-based, asteroid-dwelling animals called 'siliconies' – endearing but rather slow, awkward and pathetic creatures. These days, of course, silicon would be powering the spaceship computer, its calculations far outstripping in speed those of the captain – and its decision-making, via artificial intelligence, likely superior too. How far can the silicon revolution take us – or, more chillingly, itself? After little more than half a century (the first silicon chip was made in 1961) this seems only the start.

353 (2020 CE)
The weight of life: now overtaken by brick, cinder block, asphalt, concrete
UK

Towns and cities have been part of human life for most of the twelve millennia of the Holocene – part of life immemorial, one might say, certainly going back beyond the beginning of recorded history. In the Anthropocene, this near-constant of organised human civilisation has grown to exceed life itself – literally. In the mid-20th century, all the things that we build – of which the urban realm forms a major part – was outweighed some tenfold by the combined weight of all living things on Earth. Since then, the weight of life has fallen slightly, while the weight of our constructions (the functional ones, not counting the rubble of demolished ones) has grown vertiginously. In the year 2020, the weight of the manufactured human world overtook that of the living world, with both being (in dry weight, not counting water content) a little over a trillion tons. This layer of dust preserves the fruits of this achievement. Concrete takes the palm, just by itself weighing in at over half a trillion tons. That is equivalent to one kilo per square metre of Earth's surface, land and sea. Since 2007 – the year, more or less, when humans became dominantly urban-dwelling – this has become our natural environment.

354 (2021 CE)
Sinking cities: Mississippi sediment
New Orleans, USA

Some parts of the Earth's crust are rising, and some are sinking. That is quite normal, and is the way by which sediment is produced, and strata are formed. The problem comes when people build cities as if this kind of thing did not happen – and then, yet more acutely, act to magnify the sinking process. New Orleans is one of the world's classic sinking cities, sited on the Mississippi delta, the huge weight of which has been pushing down the crust for tens of millions of years. The sinking is being amplified as people draw fluids – water, hydrocarbons – from the soft delta muds, making them compact down further. Parts of New Orleans are already up to 2 metres below sea level, the sea being held back by walls. In the geological short term, it will become one of the world's drowned cities, which will be a deeply felt human catastrophe. As subsidence continues, it will become a gigantic technofossil. Mississippi sediment has a particular quality: there is not enough of it to help the delta grow back, as much has been held back, trapped by dams upstream. Global sea level is rising too, again by human action. It is a perfect storm of circumstances, to bring the sea onto the land.

355 (2021 CE)
Zombie forests
The western extent of the Stanislaus National Forest, California, USA

The trouble with the Anthropocene is that, for the foreseeable future, it is not a state of the planet, but a trajectory. The various human impacts are ongoing, and their cumulative effects – even if those impacts stopped tomorrow – will take some time to work their way through the Earth System. The living organisms and ecologies caught up in this, therefore, will carry on being affected by changing conditions, until a new equilibrium is established. We have departed from the stable state of the Holocene, that lasted some 12 millennia, and the new stable state is still far in the future – many centuries away at least, and probably many millennia. Temperatures are rising, but we do not yet know how far they will rise, or what kind of feedback effects will be triggered to slow or speed up the warming. But it seems likely that some ecologies, whether particular ones (types of forest in certain regions, for instance), or even general ones (most coral reefs in the world) are encountering climate states which they cannot survive long-term. These are the zombie ecosystems: still alive, but with doubtful prospects of remaining so as the Anthropocene trajectory continues. It is less fun than the horror films.

356 (2021 CE)
Rewilding: sample of rye from Chernobyl
Chernobyl Exclusion Zone, Ukraine

The Chernobyl accident in 1986 was the world's worst nuclear accident. The result of a botched test on an old, design-flaw-plagued reactor led to an uncontrolled chain reaction, explosion, meltdown, fire, destruction of the building and the release and airborne spread of massive amounts of radionuclides. Some 30 people died in the immediate aftermath, including heroic firemen who stabilised the situation and prevented a yet worse tragedy. The overall fatalities, from excess radiation in the wider population, are harder to pin down: estimates range from several hundred to more than ten thousand. The name of Chernobyl is one of a litany – Windscale, Three Mile Island, Fukushima – that has given nuclear power its fearful reputation. And yet, there is another side to the aftermath. The most contaminated region around Chernobyl, some 2800 square kilometres, became an exclusion zone, and more than 100,000 people evacuated. Now, in that wilderness, the forest is growing back, including in the nearby city of Pripyat. Wild boar, elk and deer populations grew quickly; the wolves returned and are thriving; there are lynx, storks, bears and bison. The rare Przewalski's horse has been re-introduced. There are still dangerous levels of radiation in the area. But for the wildlife, this is a lesser danger than that posed by humans going about their normal business. This unplanned experiment in rewilding is likely to run for centuries more – though as these lines are written, it has been violently disturbed once more, by war.

357 (2021 CE)
'Super Plants', *Arabidopsis thaliana*
California, USA

Plants have developed some quite particular uses in the Anthropocene. Take the plant with the charming name of mouse-ear cress, more formally *Arabidopsis thaliana.* Growing just a foot or so high, with thin leaves and small flowers, it is neither very tasty nor very nutritious (it is technically edible, or at least not poisonous, but is mostly considered a weed). Nor does it produce textiles, nor some useful kind of sap. It does produce knowledge, though, and this in very large amounts. Its qualities here are that it grows and reproduces quickly, has translucent tissues – all the better to study using a microscope – and has a small and simple genome. Thus, it has become an experimental plant *par excellence*: that is, a plant that is studied by biologists to find out how plants in general – and to some extent how life in general – function. It is the first plant to have its entire genome sequenced, in 2000, and in 2019, it was taken to the Moon aboard the Chinese Chang'e-4 lunar lander. There, together with silkworms and potatoes, it will – the scientists involved hope – be persuaded to form a tiny, viable ecosystem. So, it's a weed that is reaching for the stars – but it stays thoroughly down to Earth, too. On this planet, scientists hope to modify it to take carbon from the air and store it underground, as one means of helping deal with the climate crisis. A superplant, indeed.

358 (2020 CE)
Synthetic diamond, 140/170 grit loose powder
USA

Making a diamond is quite hard work for nature, on this planet at least. To squeeze carbon atoms down into that ultra-tough cage-like molecular structure, one needs pressures usually attained some 200 hundred kilometres down, within the Earth's mantle. And then comes the even more difficult journey back to the surface, via rare, gas-charged kimberlite eruptions that can blast a passage from that depth to the Earth's surface. Diamonds can form on Earth in a few other ways, such as in gigantic meteorite impacts, though these only produce microscopic diamond specks. The human world, though, has sufficient ingenuity to make synthetic diamonds – which are made at low pressures, from a methane-bearing plasma in a laboratory – to the tune of about a thousand tons a year. These are generally not for jewels, though, but find use as industrial abrasives.

359 (2022 CE)
Digital traces: DNA hard drives
USA

The evolution of the silicon chip of the past sixty years has been one of the most astonishing, and the most consistent, phenomena of the Anthropocene. The 'law' predicted by Gerald Moore that the number of connections on a silicon chip would double every two years – and so computers and all that they do would double in performance and power every two years. Moore originally thought that this pattern might hold for a decade, before hitting a brick wall of technical impossibility. But, decade after decade, those brick walls have been smashed through, by engineering wizardry and huge investment, and only now is Moore's Law beginning to stall, as it hits physical limits. It has, though, brought us the still furiously evolving, ever smarter, ever more interconnected electronic cocoon that now both nurtures and imprisons us. But new horizons are being sought. The original recorder and transmitter of complex information is the DNA molecule, from some time back in the Archean, perhaps even the Hadean, eon. Could that power and complexity be harnessed to build the next generations of computer, immensely more powerful still. Potentially, DNA can pack millions of times more information into the same space as silicon. Can it be made to work? What awaits us, down this road, on the undreamed shores of the technosphere?

360 (2022 CE)
Megacities: Fools gold/pyrite
Peru

How does one make a city with streets paved with gold, in the Anthropocene? The answer is simple, and now inevitable. You drown it, and here the gold that forms is pyrite, otherwise known as fool's gold. As sea level rises to begin to submerge coastal cities (these days it is likely to be coastal megacities, the number of which has risen something like twenty-fold since 1950) the water will inundate our insanely complex infrastructure, first below ground – metros, sewer systems and such – and then the collapsing wreckage above ground. And there is a *lot* of this infrastructure, which has recently come to outweigh the living biosphere (just the functional parts, that is – the stuff we have discarded is several times the mass of that again). In ancient strata, fossils such as ammonite shells were submerged, oxygen-deprived spaces in which it was easy for iron and sulphide ions to diffuse in, to crystallise as pyrite and give the fossils that beautiful golden coating. Within drowned cities the spaces for this kind of mineralisation will be bigger, more various, often more intricate. In the circumstances, fool's gold will be a most appropriate chemical epitaph.

361 (2022 CE)
Soy beans from the Amazon rainforest, which may be lost in our lifetimes
Brazil

What price is a hamburger? We are creatures of our appetites, there are very many of us, and the consequences of this conjunction stretch very far. Soybeans are highly nutritious but, for many, less tasty than beef – even if in feeding soybean to raise cattle before feeding the cows to us, most of its energy is lost. The product of this equation, as resolved in millions of human hearts, for now, is that the Amazon rainforest is shrinking rapidly, and the land devoted to this kind of agriculture is growing. This is not only destroying one of the great cradles of Earth's biodiversity, but also transferring its carbon store from the land into the air. More: the process is undermining the very possibility of growing rainforest on the land, for that forest, in transpiring vast amounts of water through its leaves, is its own rainmaker. Remove it, and the climate will become too dry for rainforest, and convert to grassland – irreversibly, as far as human timescales are concerned. It is one of the tipping points in the Earth System that is becoming closer.

362 (2022 CE)
Anthropogenic carbon: human-made carbon removed from the ocean
Los Angeles, USA

What can we do with all the carbon dioxide that we have taken from the ground and put into the atmosphere and oceans? It is beginning to cause great harm – heating, de-oxygenating and acidifying the oceans, melting polar ice, raising global atmospheric temperatures and changing weather patterns. Technologically extracting some of our carbon pollution out of the air is possible – but cumbersome and expensive. This layer in the artwork contains the results of an experiment that tries a different approach, extracting carbon from the sea by making synthetic limestone chemically from seawater (which, if produced in large amounts, might be used to build the cities of the future). Can it be made to work? How much would it cost, to make any significant difference to climate? What are potentially harmful side-effects? These are the kind of questions that emerge, as we try to devise means to cope with the predicament that we have found ourselves in.

363 (2022 CE)
Fallen branches from the ginkgo child trees of Hibakujumoku, survivor trees from the Hiroshima bombing
Japan

On August 6th 1945, the fireball from the atomic bomb dropped by a US warplane on Hiroshima killed some 150,000 people and razed the landscape. Just a couple of kilometres from the centre of the blast grew 170 ginkgo trees, in full leaf. Scorched and blackened, stripped of leaves, massively irradiated – yet the living core of these trees somehow survived, to allow them to flower again next spring, while most of the area remained a biological desert. Ginkgos are survivors. They have survived from their heyday in the times of the dinosaurs, despite being reduced, during the climate rollercoaster of the Ice Ages, to just handfuls of trees in China. From there, they got a helping hand from humans: transplanted to Europe, to America, to Japan. The ginkgos that were grown in Tokyo underwent their own test, in the enormous fire that followed the great 1929 earthquake. Their resilience in that conflagration was what led them to be planted in Hiroshima. Now, the child trees of those survivor ginkgos are growing and flowering peacefully. Let us hope that they – and we – will be spared the ordeal their parents endured.

364 (2022 CE)
Rebirth of a species?: *Partula suturalis*, snail (extinct in the wild)
Moorea, French Polynesia

Tahiti and the other Polynesian islands used to harbour many distinct species of the small tree snail *Partula.* Then came the kind of story that is all too familiar, as regards shaping the Anthropocene landscape. A much larger snail, the African land snail, was then introduced as food for people – but the African snails did only too well: they escaped, and began to eat crops. To control them, a predatory snail, *Euglandina rosea*, was introduced in 1974. This, though, began to prey on the local *Partula* snails, and soon drove some 50 of the original 125 species into extinction. There are, alas, many stories like this from around the world, as consequence of the spread of invasive species. A couple of dozen of the surviving *Partula* species only survive in captivity, a zoo now being their lifeline. Genetic material from them – and for many other endangered species – is now being stored, too. In one initiative, the Frozen Ark, tiny blood samples are 'cryopreserved' on a kind of specially designed blotting paper, to be stored indefinitely at ultra-low temperatures. Originally designed for the far future, the material can be used, even now, to help restore genetic diversity in such tiny surviving populations. At this critical time for life on Earth, the biosphere needs such a sense of care and ingenuity to grow in human hearts.

Acknowledgements

Requiem by Katie Paterson is a new commission by the National Glass Centre as part of the Glass Exchange project, and Ingleby Gallery.

Text by Jan Zalasiewicz, Emeritus Professor of Palaeobiology, University of Leicester.

Sincere thanks to:

Tom Adam

Claudia Agnini, Associate Professor, Department of Geosciences, University of Padova

Professor Alexandre Anesio, Department of Environmental Science, Aarhus University

archiREEF

Lisa C. Barber, Cartographer, University of Leicester

Julia Barton

Professor Liane G. Benning, Department of Earth Sciences, Free University of Berlin

Robert R. Bensley, Distinguished Service Professor of Organismal Biology and Anatomy, The University of Chicago

Rachel Bronson, President and CEO, the Bulletin of the Atomic Scientists

Martin John Callanan

Rachel Carson

Julian Charrière

Professor George Church, Founding Core Faculty & Lead, Synthetic Biology, Wyss Institute at Harvard University

Dr. Maarten Christenhusz, Royal Botanic Gardens Kew

Cutty Sark, Royal Museums Greenwich

Shamik Dasgupta, Associate Professor, Institute of Deep Sea Science and Engineering, Chinese Academy of Sciences

Durham Cathedral

Dr. Matt Edgeworth, Archaeology and Ancient History, University of Leicester

Edinburgh Botanical Gardens

European Space Agency

David Farrier

Professor Dame Jane Francis, Director, British Antarctic Survey

Camille François, Commission for the Geological Map of the World

Simone Galeotti, Associate Professor, Department of Earth, Life and Environmental Sciences, Università degli Studi di Urbino

Galloway Fisheries Trust

Genewatch UK

Geological Survey of Denmark and Greenland (GEUS)

Professor John I. Glass, Leader of the Synthetic Biology & Bioenergy Group, J. Craig Venter Institute (JCVI)

Professor Emeritus Felix Gradstein, University of Oslo, Museum of Natural History (Geology)

Dr. Nathalie Grassineau, Department of Earth Sciences, Royal Holloway University

Jay Griffiths

Dr. Sean P.S. Gulick, co-director of the Center for Planetary Systems Habitability, Jackson School for Geophysics

Gloria Hampel

Dr. Tom Harvey, School of Geography, Geology and the Environment, University of Leicester

Dr. Robert Hazen, Mineralogist and Astrobiologist, Geophysical Laboratory, Carnegie Institution; and Executive Director, Deep Carbon Observatory

Dr. Sebastian Hennige, School of GeoSciences, the University of Edinburgh

Avery Hill, Global Ecology & Climate Solution Lab, Biology Dept, Stanford University

Florence and Richard Ingleby, Ingleby Gallery

C. Brenhin Keller, Assistant Professor, Department of Earth Sciences, Dartmouth College

Distinguished Professor Emeritus James Kennett, Earth Science, UC Santa Barbara

Dorothee Kirch, NYLO, The Living Art Museum, Iceland

Fiona Lee, artist, climate justice activist and bushfire survivor, New South Wales, Australia

Siobhán Maguire

Andri Snaer Magnason

James Maskrey, National Glass Centre, Sunderland Culture

David R. Montgomery, Professor of Earth and Space Sciences, University of Washington

NGO Shipbreaking Platform

Professor Euan Nisbet, Department of Earth Sciences, Royal Holloway University

Jeff Nivala, Principal Investigator, Allen School of Computer Science and Engineering, University of Washington

Object and Ideograms

Olkiluoto nuclear-waste repository

OVEC: the Ohio Valley Environmental Coalition

Památník Terezín (Terezín Memorial)

Isabel Paterson

Mie Thorborg Pedersen, Department of Green Technology, SDU Biotechnology, Denmark

Richard Phillips, Higher Predators and Conservation group, Core Science Ecosystems, British Antarctic Survey

Orrin H. Pilkey, James B. Duke Professor Emeritus of Geology, Division of Earth and Ocean Sciences, Nicholas School of the Environment, Duke University

Professor Simon Poulton, Chair in Biogeochemistry and Earth History, School of Earth and Environment, University of Leeds

Neil Rose, Professor of Environmental Pollution and Palaeolimnology, Environmental Change Research Centre, Department of Geography, University College London

Royal Botanic Gardens, Kew

Dr. Adrian Rushton, Department of Earth Sciences, Natural History Museum, London

Dr. Catherine Russell, School of Geography, Geology and the Environment, University of Leicester

Salk Institute for Biological Studies

Professor Gaurav N. Sant, Samueli School of Engineering, UCLA

Save the Children

Professor J.T. Smith, School of Environmental, Geographical and Geological Sciences, University of Portsmouth

Julia Stephenson, National Glass Centre, Sunderland Culture

The Anthropocene Working Group

The Chernobyl Spirit Company

The Frozen Ark

The HALO Trust (Hazardous Area Life-support Organization)

The Institute for Carbon Management, UCLA

The Tyre Collective

Dr. Simon Turner, Department of Geography, University College London

Dr. Benjamin A. Ubleble, Centre for Environment, Human Rights and Development (CEHRD), Port Harcourt

Marcos Castellanos Uribe, School of Biosciences, University of Nottingham

Professor Bruce Whitelaw, Genus Personal Chair of Animal Biotechnology, The Roslin Institute, University of Edinburgh

Dr. Scott L. Wing, Research Geologist and Curator of Paleobotany, Smithsonian National Museum of Natural History

Wellcome Sanger Institute

WWF

Dr. Shuhai Xiao, Professor of Geobiology, Department of Geosciences, Virginia Tech

Jan Zalasiewicz, Emeritus Professor of Palaeobiology, University of Leicester

Professor Jens Zinke, Professor in Palaeobiology, School of Geography, Geology and the Environment, University of Leicester

Design by Joanna Deans

Printed on 100% recycled paper

www.katiepaterson.org
www.inglebygallery.com
www.nationalglasscentre.com