

DARWIN'S LOST WORLD



The Hidden History
of Animal Life

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PREFACE

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Some 150 years ago, in 1859, Charles Darwin was greatly puzzled by a seeming absence of animal fossils in rocks older than the Cambrian period. He drew attention to a veritable Lost World that was later found to have spanned more than eighty per cent of Earth history. This book tells the story of his lost world, and of the quest to rescue its hidden history from the fossil record.

Intriguingly, such a quest did not really begin until 1958, some hundred years after Darwin. Why did an understanding take so long? Arguably it was because it was, and still remains, a very big and very difficult problem. Its study now involves the whole of the natural sciences. Progress has been a matter of slow attrition. For most of this time, for example, there has been no concept of the vast duration of Precambrian time, nor any evidence for a distinct biota.

This book follows the story of my own research history, beginning with a cruise as Ship's Naturalist on *HMS Fawn* studying Caribbean marine ecosystems. Like my own researches, it then pushes ever further backwards through time, from an inquisition into the nature of the Cambrian explosion and the enigmatic Ediacara biota some 600 to 500 million years ago, towards the

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emergence of the earliest complex cells some 1000 million years back. Each step backwards in time has drawn me towards ever more remote and little known parts of the planetary landscape, and towards equally puzzling parts of the human mental landscape. I have therefore sought, in each chapter, to put some of the major questions into context by descriptions of premier field locations from around the world, enlivened by descriptions of their fossils, their fossil hunters, and their puzzles.

My hope is that the book will show just how rich and diverse have been our ways of thinking about the earliest life forms, written in words that can hopefully be read with ease and enjoyment. Good science is, after all, not just about facts. It should be a form of play. If a thing is not playful, it is probably not good science. Each generation has therefore come up with its own favourite solution to the question—*whence cometh life?*—only to watch it fall as the next generation of science and scientists has arrived on the scene and found even better solutions. Deep down, my hope is that the book will show how my subject works as a science, how the questions are being shaped, and how the early fossil record of animal life may yet be decoded, bringing the world of ancient and modern life right to the doorstep of all those who are curious and wish to learn about the rich history of life beneath their feet.

Here, then, is your passport to becoming a Time Traveller, and to making your own exciting discoveries about the world in which we really live. The fossil record is your best guide for decoding pattern and process and the meaning of life. And the starting point for the reading of patterns is your own natural curiosity spiced with a modicum of *doubt*. Happily, science is a uniquely valuable system for the measurement of doubt.

CHAPTER ONE



IN SEARCH OF LOST WORLDS

Darwin's Great Dilemma

It is January, 1859. Imagine being a visitor, seated on a sofa in Darwin's large and dark study at Down House in Kent. The Christmas decorations have been put away. The smell of leather-covered books, gas lamps and moth balls rises up from the walls of this well-used room. Over the past few months, our world-weary naturalist has been drawing together the last remaining thoughts for his new work, to be called 'On the Origin of Species'. Its contents have been gathered from notes and observations made since 1831, an epic of nearly thirty years' gestation.

At first, we see him sitting in his easy chair, scratching away eagerly upon a board resting on his knee. We expect him to look engrossed and satisfied, and for a while he does. But suddenly, he looks up and scowls and then starts to pace nervously around the room, tapping the palm of his hand with a pen. After a minute, he stops to pick up a fossil trilobite from the mantle shelf. It is one of the oldest animal fossils known from the geological record. Looking like a little woodlouse trapped within layers of black slate, it is without any eyes—a completely blind trilobite. Teasingly called *Agnostus*, its name could be taken to mean 'without a knowledge

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of God'—blind to the Creator. Darwin turns this offending fossil over and over, as though searching for something. He then lets out three words, with a hint of genteel exasperation: 'Inexplicable . . . absolutely inexplicable.' With that, he sits down to write this phrase on his notepad: '*The case at present must remain inexplicable; and may be truly urged as a valid argument against my views here entertained.*'¹

Our story begins here, with this great puzzle set in 1859 (see Plate 1). Charles Darwin clearly disliked the mad rush to publish 'On the Origin of Species'. It was full of risks to his reputation, to his health, and to his peace of mind. He had spent many a restless night, worrying over the shape of the arguments in each chapter, checking and rechecking the language to ensure that all the sentences sounded authoritative, measured, and balanced. Like many a scientist driven unwillingly towards the arena of public debate by the adrenalin of a new discovery, he had no doubt been hearing the voices of his enemies hissing at him, like gas lamps in the quiet of the Victorian evening. And by 1859, Darwin had made a rather splendid enemy. His nemesis was the eminent scientist, Richard Owen, a highly intelligent, outspoken, ambitious, and more than usually unpleasant Victorian anatomist. In appearance, Owen was dark, dapper, striking and to our modern minds, perhaps, rather sinister-looking—a kind of Professor Moriarty from the Sherlock Holmes stories.² More to the point, Owen boasted a brace of good connections. He was Superintendent of Natural History at the British Museum, a Member of the Athenaeum Club, and close to the bosom of the Royal Family. He was also famously arrogant, taking great pleasure from sneering at intellectual competitors such as Darwin. The latter had written bitterly to a friend that Owen was being 'Spiteful . . . extremely malignant, clever, and . . . damaging' towards him.³

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But publication of the *Origin of Species* by Darwin, however distasteful, had become unavoidable, ever since Alfred Russel Wallace had written to him from the jungles of the Moluccas. Both naturalists had, quite independently, stumbled upon the same, dangerous and earth-shattering, conclusion: that natural selection causes new species to form and life to evolve with time. And that this simple process, operating alone in nature, is the Rosetta Stone that helps to explain most of the diversity of life, both present and past.⁴

To win the argument on evolution back in 1859, Darwin needed to point not only to a plausible pattern but to an ultimate 'first cause' for evolution. He had indeed stumbled upon a stunningly simple 'first cause', natural selection, that does away with supernatural involvement in the diversification of life 'from simple beginnings'. Like a flock of fledglings flying home across a storm-tossed sea, Darwin had observed that only the strongest and fittest within a living population will survive to the end of their journey. He had identified that life was a race against endlessly winnowing forces, like flying against the rain, the wind, and the waves.⁵ But he could not explain why these populations varied—nor, indeed, how such variation was transmitted from one generation to the next.

The flock of young birds is merely our metaphor, of course. What was needed by Darwin was something more concrete—an appropriate set of biological experiments, something easy to study and close at hand. Something from the dinner table, perhaps. Interestingly, he decided to settle upon viands from the Sunday roast for tackling this question. But he had inadvertently chosen the wrong dish, working upon fancy homing pigeons rather than upon garden peas. A Moravian monk named Gregor Mendel was shortly about to discover the rules of genetics from his experiments on pea plants over a series of years in the monastery gardens.⁶ Unfortunately

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Darwin knew nothing of this work. And quite a lot was still worrying him—he had found evidence for the workings of natural selection, but could not explain the mechanism of inheritance. Nor could Darwin yet point to any detailed evidence for evolution in the fossil record.

As if these were not problems enough, the greatest puzzle facing Darwin was actually rather shocking. An inexplicable surprise was just beginning to emerge from within the geological record itself: the greater part of the rock record appeared to preserve no physical evidence for life on Earth at all.⁷ That is to say, no geologist back in 1859 was able to point to any convincing kinds of fossil in the most ancient rocks on Earth, which today we call the Precambrian rocks. There were no clear animal fossils below the trilobites. Older rocks remained oddly silent. That would not matter much if the Precambrian was only a short period of time. But, as we shall shortly see, Darwin knew that this 'silence' was no brief aberration. It had spanned the greater part of Earth history.⁸

Just how long ago all this took place, or rather didn't take place, also became part of a nightmare for Charles Darwin. In early editions of the *Origin*, he had implicitly been thinking of many hundreds of millions of years ago. But by the sixth edition of 1872, he obviously felt a bit rattled:

Here we encounter a formidable objection; for it seems doubtful whether the earth, in a fit state for the habitation of living creatures, has lasted long enough. Sir W. Thompson [Lord Kelvin] concludes that the consolidation of the crust can hardly have occurred less than 20 or more than 400 million years ago, but probably not less than 98 or more than 200 million years. These very wide limits show how doubtful the data are; and other elements may have hereafter to be introduced to the problem. Mr Croll estimates that about 60 million years have

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elapsed since the Cambrian period but this, judging from the small amount of change since the commencement of the Glacial epoch, appears a very short time for the many and great mutations of life, which have certainly occurred since the Cambrian formation; and the previous 140 million years can hardly be considered as sufficient for the development of the varied forms of life which already existed during the Cambrian period.⁹

Fortunately, both Mr Croll and Sir W. Thompson were to prove very wide of the mark indeed. Thanks to the twentieth-century discovery of radiogenic isotopes, which can be used to date rocks accurately, we now know that Precambrian rocks must have been laid down during the first 80 per cent or so of all of Earth history, from about 4560 to 542 million years ago. Cambrian and younger rocks, with all their fossils—from trilobites and ammonites to dinosaurs and ape men—therefore provide little more than a footnote to the history of our planet. When Victorian geologists crossed over that threshold which we now call the Precambrian–Cambrian boundary,¹⁰ nearly everything appeared to change. Not least among these revolutions was the astonishing observation that nearly all major animal groups appear rapidly in the fossil record, within just a few tens of metres of rock, or just a few million years. That is to say, complex animal life seemingly appeared almost ‘overnight’ in geological terms. This paradox, of a long period without known life (then called the Azoic) followed by a rapid revelation of fossils (now called the Phanerozoic), must have felt like a cruel challenge to Darwin in 1859. Only the maddest of French Republican scientists would have dared to contemplate this as a bloody revolution *within* the history of life. It was so terribly . . . un-English.

Darwin was therefore forced to concede that this seemingly abrupt appearance of complex animal life near the beginning of the Cambrian, now called the Cambrian explosion, could be seen

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as a major stumbling block for his evolutionary theory—a mystery that some have called ‘Darwin’s Dilemma’.¹¹ Worse still, the puzzle of Darwin’s missing fossils could be seen as evidence for the act of Creation itself. That was Sir Roderick Murchison’s view, although his mentor Charles Lyell was trying to keep an open mind on the matter. Darwin was therefore careful to speak in very cautious terms within the *Origin of Species* about the absence of any fossil ancestors or obvious intermediates between the known animal groups. He postulated a ‘lost world’ too dim to make out through the mists of time:

There is another and allied difficulty, which is much graver. I allude to the manner in which numbers of species of the same group, suddenly appear in the lowest known fossiliferous rocks . . . I cannot doubt that all Silurian trilobites¹² have descended from some one crustacean, which must have lived long before the Silurian age, and which probably differed greatly from any known animal¹³ . . . Consequently, if my theory be true, it is indisputable that before the lowest Silurian stratum was deposited, long periods elapsed, as long, or probably far longer than, the whole interval from the Silurian age to the present day; and that during these vast, yet quite unknown, periods of time, the world swarmed with living creatures.¹⁴

Evidence from a living Lost World

Darwin believed that life had existed in periods long before the Cambrian, and that fossil evidence for this would eventually be found. On *HMS Beagle*, he had to content himself with clues about the early history of life gathered from the islands of the Galapagos. For many a budding scientist in later times, their dream was to discover another Lost World, revealing the deeper

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history of Life. It was certainly mine, ever since picking up a copy of Sir Arthur Conan Doyle's adventure story of the same name, about a scientific expedition that set out to discover long-lost life forms living on a plateau hidden deep within the jungles of South America.¹⁵ And in 1970, I was to have the chance to explore for myself just such a lost world. Shortly after graduating, and to my considerable surprise, I found myself as Ship's Naturalist, lying in a bunk aboard *HMS Fawn*, sailing out of Devonport dockyard behind *HMS Fox*, and bound for the Caribbean.¹⁶ The *Fawn* was a sleek white surveying ship of 1160 tons displacement, with a buff coloured funnel and gleaming teak decks. Stirringly, she was also a successor ship to *HMS Beagle*. When I joined her in the Naval Dockyards at Devonport, she and her sister ships (*HMS Fox*, *Beagle*, and *Bulldog*) were the pride of the Hydrographic Division of the Royal Navy.¹⁷ *Fawn* even looked like a millionaire's yacht—especially when at anchor in a Cayman lagoon on a moonlit night.

Our brief was to chart reefs and lagoons, and to gather together an environmental rollcall of marine life from this unspoilt portion of Paradise. In particular, our plan was to make detailed charts of two great natural hazards to shipping in this dwindling pond of the British Empire. One of these was a huge island that no one alive had ever seen, called Pedro Bank. For most of the geologically recent past, Pedro Bank had been an island as big and as lush as Jamaica. But nobody has ever seen it because it sank beneath the waves some ten thousand years ago, at the end of the last Ice Age, like the legendary Atlantis. The second hazard was another large lost island, called the Barbuda Bank. This lay just to the north of Antigua, where Nelson had his harbour, as for a while did we.

The sea, the sky, the bone-white beach and zesty afternoon breeze lightened our daily chores of sampling and echo-sounding on board ship. Long spells at sea were punctuated by lively visits to

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friendly island states scattered between the Orinoco and Florida. For one month, we were even sent on a mission to clear the Bahama Banks of pirates. President Fidel Castro had complained to the British Government that the north coast of Cuba was being raided by pirates who were holed-up in some remote islands of the Bahamas. Our governmental response was to send in the Royal Navy.

Suddenly, we had to abandon the making of charts and the measuring of dainty sea shells, to take up rifle practice. As night fell, we would scan the radar for signs of unexpected vessels. One night, at last the cry went out—a suspicious object had indeed been spied, floating in the water about one hundred yards to starboard. Off went the search party to tackle this dark menace: illegal lobster pots, dozens of them, filled with tasty crayfish. We dined royally for a week. No pirates were ever seen of course—we were careful to make far too much noise for that.

The Bearded Lady

I had been at sea on board HMS *Fawn* for five months before my Galapagos moment arrived, in August 1970. My 'Galapagos' was to be Barbuda, at that time one of the most unspoilt islands in the tropical Atlantic.¹⁸ This name will make any Spanish speaker smile, because it means, quite literally, 'the bearded lady', perhaps in reference to its jutting goatee of storm beaches. Christopher Columbus never saw Barbuda because it is so very low lying and easily concealed behind the Caribbean swell. Indeed, this invisibility makes it one of the greatest navigational hazards in the region. Later seafarers also largely ignored Barbuda because its soils are poor and thin, and its climate distinctly arid. There is some vegetation, of course, but much of it is little more

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than a wilderness of Turk's Head cactus, sword-leaved *Agave*, manchineel, and mangrove. The island has little farming, and only a thousand souls then lived in its single settlement called Codrington, making a modest living from conch and crayfish in the surrounding reefs and lagoons.

My own dream during the cruise of *HMS Fawn* was to see how the evolutionary and environmental history of modern reefs and lagoons might be traced backwards in time, using proxies from the fossil record. Was that even remotely possible? That August, a quick encirclement of the island on foot and horseback showed that four main features make up the primeval scenery of Barbuda: the highlands and the lowlands, the lagoons and the reefs (see Figure 1).

First, and most ancient, is that remote plateau of limestone—called the Highlands—which rises up sharply, 100 feet or so, above the jungle. When I first set foot on the island, there was no proper road out from the little village of Codrington towards this mysterious plateau, which was then so densely vegetated that it was almost impassable without a cutlass. Seeing this for the first time was, indeed, like having a private invitation to explore Conan Doyle's Lost World.

These Barbudan Highlands are surrounded by a diadem of salt lakes and lagoons, strung out along the western or leeward side of the island—over a dozen of them, some active, some ancient, and each of them home to a distinct menagerie of plants and animals. The greatest of these salty lakes is called Codrington Lagoon, which is some three kilometres wide and ten or so kilometres long, and connected with the open ocean to the north by means of a long and winding tidal channel. Branching off this main body of water, we found a series of smaller lagoons. Each of these smaller lagoons is separated from its neighbour by a narrow beach of pink

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Figure 1. A Living Lost World. Map of the tropical island of Barbuda, in the eastern Caribbean, where the author began his researches into Darwin's Lost World. The Caribbean Sea lies to the west, and the main areas of coral reef (shaded in black) face the Atlantic Ocean to the east.

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and white sea shells, often with its own distinctive character. There would be mangrove and frigate birds on one ridge, coco palms and giant mosquitoes on another, and so on. Most days, the only craft we would see while mapping this watery wilderness was a schooner sailing down the main lagoon, bringing the much needed weekly rations from Antigua.

Around Barbuda lie three reef tracts, each sheltering the island from the annual tropical storms and their steaming white breakers. These reef tracts were then some of the finest in the whole of the tropical Atlantic; vigorous because of the huge oceanic swell that pounds across them. Indeed, there is almost no part of the island where you could not hear the distant boom of waves thundering across the reefs. A hair-raising roar would therefore assault us as we approached the reefs for mapping each morning. The main fringing reef of the island is some fifteen kilometres long and clings to the rocky shoreline along much of the eastern seaboard. To the north and south of the island, the fringing reef fans out into luxuriant reef gardens, bathed in waters as warm and clear as a baby's bath. These coral reefs conceal a darker harvest, however—a scattering of some 200 shipwrecks. But both algae and corals delight in shipwrecks—they use them to build upwards and outwards along the tract.

It was tempting to share the rapture felt by young Charles Darwin as I escaped the claustrophobia of *HMS Fawn*, after many months spent at sea with her strict routines, stuffy protocols and endless meals of boiled cabbage, and sailed away in a small boat towards my tropical island. But whereas the young Charles Darwin spotted oddities in birds and land turtles across his islands, that is to say, in terms of *space*, I was, in my modest way—and I had much to be modest about—preparing to stumble upon some oddities in terms of *time*.

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In a grain of sand

During the last quarter of 1970, we mapped the distribution of microbes, plants, and animals around the island. Days would typically begin at dawn, speeding with companions across the lagoon in our motor boat, followed by snorkelling and sampling in some hitherto unexplored part of this watery Eden.¹⁹ Work would continue in the boat until mid afternoon, when the trade wind got too strong for comfort. We would then make our way back towards the little jetty in the south-east corner of Codrington Lagoon, to beach the boat before brewing up for afternoon tea.

Back in the village, we had set up a little laboratory within an abandoned cotton mill—called the Ginnery—right next to the lagoon. In these hot and windy afternoons onshore, we would pack our sample jars, full of pink sand and gaudy shells, in readiness for shipment back home. In the gloom of the evening, a hurricane lamp provided a modicum of light for us to find our way around inside the dingy warehouse. The tinkle of Gladwin Nedd's Steel Band would then waft through the evening air from the Timbuck-One Saloon, and we would watch our lamp being dive-bombed by a squadron of moths, mantids, and beetles. Not that we were safe from arthropod attack during the day. More venomous creatures were on the prowl around the Ginnery than we could ever hope to see. One morning for example, on getting out of my camp bed, I jumped into my shorts a little too hastily. Just as I was pulling them on, I spotted a fluffy Tarantula spider nestling comfortably in the gusset. We kept 'Tara' in a jar for months. But while tarantulas and giant centipedes seemed to be crawling everywhere, we gradually learned to keep them out of the shower and, most importantly, from under the toilet seat.

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It was within this little zoo that was I able to set up a small binocular microscope and study living and fossil shells from around the island. The gathering and identifying of plants, sponges, corals, and seashells began to mount as the weeks turned into months. By late September, we had collected and mapped dozens of different types of organism across the floor of Codrington Lagoon.²⁰ A stunning surprise, though, was the sheer abundance and variety of life that became visible when I started to look down the barrel of my microscope. The diversity of little shells seemed to multiply logarithmically every time the level of magnification was raised. For example, a square metre of lagoon or reef would visibly support a dozen or so species of macroscopic mollusc shells. But there was vastly more variety and abundance when the lens was racked down to shells just a millimetre or so across. And another huge increase in diversity emerged when I scanned the microscope down to creatures less than a tenth of a millimetre wide, many of them of exquisite beauty (see Plate 2). One thing was beginning to become clear: there is a 'fractal' quality to the biosphere.

When I got back to the old Cotton Ginney each afternoon, I would set about 'seeing this little world in a grain of sand'. One of the first things to be tested was the number of species present within a 'teaspoon' of sand and mud from Goat Reef. In a sample of seafloor, as bleached and unremarkable as a patch of sand from the Arabian desert, almost ten thousand individuals and a hundred species of foraminiferid protozoans were present. And this count did not take into account any of the other tiny creatures or the nearly invisible microbes. At that time, little could really have prepared me for this surprise, but something similar is now known to hold true across the whole of the natural world. It is called the biological scaling law: there

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are lots of little creatures and progressively fewer large ones. If I was going to trace the history of life back into deep time, it would clearly be wise to forget about dinosaurs. It was the smaller creatures I would need to watch.

On Goat Reef

Looking east from the beach towards the reef tract of Barbuda, the great Atlantic rollers appear as a long white ridge that dances up and down on the skyline. These waves are symptoms of the trade winds that refresh this part of the tropics. Under such conditions, the coral formations are sculpted into buttresses and shelves, corridors and caverns of all shapes and sizes. Some parts of the reef are to be found extending their branches up into the sunshine while others lurk in self-made gloom. Each part of the reef therefore has its own biota, with light-loving corals and algae thriving on the sunlit tops, and shade-loving sponges and protozoa nestling down in the dim recesses. One morning when we brought pieces of this living rock up into the boat, I was rather surprised to find it full of holes—circles and slits, tubes and tunnels of all shapes and sizes. These caverns are entirely natural, of course, providing homes for a rich menagerie of invertebrates, such as yellow sponges, pink sea squirts and purple brittle stars. The more holey the habitat, it seemed, the richer was the tally of life. There was truth, after all, in that old saying: life is a search to maintain surface area.

The chief architect of this reefal framework is a coral called *Acropora*, the elk horn coral. In fact each elk horn is built by a colony of genetically identical coral polyps, natural clones that form colonies which may be some hundreds of years old. Diving around elk horn coral can be a dangerous and painful enterprise:

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not only can the tiny corallites inflict painful rashes in the epidermis, much like a jellyfish sting, but their hard and chalky constructions will shred human skin like a knife, given half a chance. It does well to remember that elk horn corals have torn out the bowels of many a ship, allowing the reef to dine at night upon sailors.

Biologists have for long realized that corals like *Acropora* are cnidarians—cup-shaped animals with a flower-like radial symmetry. All cnidarians are provided with a simple but very effective survival kit: tentacles with stinging cells plus a seemingly unhygienic but effective gut: there is no anus. The coral has therefore to eject its waste through its single opening, called the mouth. Hence, in terms of the tree of life, cnidarians are regarded as relatively primitive animals. Indeed, only the sponges are thought to branch lower down on the tree.²¹ Another remarkable feature about reef-building corals is the way that they feed. Each tentacle is equipped with tiny stinging cells that are primed to harpoon small animals as they pass. Corals are particularly adept at catching zooplankton, tiny crustaceans and animal larvae that lurk in the depths during the day but come up to feed in the water column at night.

The inner layers of coral polyps along the reef crest can also appear like a commercial greenhouse, with rows of simple plant-like cells that have been enticed from the water column. In the natural state, these plant-like cells show flame red pigments and bear whip-like threads that make them twist and turn in the ocean like whirling dervishes. Hence their name ‘terrible whips’ or, more correctly, dinoflagellates. This group, when let loose on their own, can cause the equally alarming ‘red tides’, which not only poison commercial shell fish with toxins but also cause mass mortality of fish and sea birds.

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Dinoflagellates are attracted to a life within corals by a seductive offer of *Free Fertilizer!* But they are then obliged to repay this debt, day-in day-out, by gratefully churning out food for the coral with the aid of captured sunbeams. Both creatures benefit from this symbiosis, it is true.²² It is a little hard, though, to say whether the relationship is like a marriage, or like slavery. My suspicion is the latter. Such sweated labour underpins the ecology of the whole coral reef, which has become dependent upon a trickle-up effect of nutrients passed along from symbionts to their hosts and thence to the next food layers.

The underside of elk horn skeletons are commonly devoid of living coral polyps. These bare patches provide valuable space for other creatures that are trying to make a living from the reef. Some of these will drill their subterranean dwellings into the old coral rock. Occasionally, they get a little too successful and cause the coral heads to collapse on to the seabed, where they will finally crumble into coral sand. Others have the opposite effect, of binding old coral skeletons together through the addition of new chalky layers. Coralline algae are famous for defending, in this way, the whole reef edifice against the ravages of time and tempest.

But one of these heroic reef binders is not an alga. It is a ruby red protozoan, a single-celled foraminiferid called *Homotrema rubrum*. This tiny beast also has a charming way of feeding. It extends jelly like threads, called pseudopodia, out of its little red shell into the surging seawater and, biding its time, it garners passing sponge spicules from the water column. Each spicule is shaped like a tiny glass needle. *Homotrema* can therefore use it as a kind of fishing rod, allowing its pseudopodia to stretch out into the warm water to entrap tasty food particles. Man may be a tool-maker. But even a protozoan can make good use of a toolkit.

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Foraminifera like *Homotrema* are thought to lie below the base of the tree of animal life. That is because they are single-celled, with neither tissues nor organs of the kinds found in true animals. But they do share, with animals, a fancy for feeding on other living matter. In other words, *they like to eat things*, especially bacteria. And while they may be of rather lowly status, they make up for this by being astonishingly abundant. They can form as much as 90 per cent of deep sea floor biomass in polar waters, and can flourish as rock forming microbes from the top to bottom layers of the ocean water column. *Homotrema* is therefore like a partner in an illustrious family business. So successful is this little creature today, that its ruby red shells enrich the ivory white detritus of the reefal shoreline, glowing like little red jewels, to the delight of beachcombers.

Down the Emerald Lagoon

Climbing back into the boat and speeding back down the channel towards Codrington Lagoon, where the sheltered waters are seldom more than neck deep, it is easy to spot a progressive change that takes place in the seafloor. Reef-building corals begin to disappear from the sea bottom when we reach the tidal channel, presumably because the waters here can become far too salty, owing to evaporation on hot and windy afternoons. An expansive surface area for life is, however, maintained in other ways: by the fine-grained nature of the muddy sediment; by kilometre-long submarine banks carpeted with Turtle Grass and Neptune's Shaving Brush (a fibrous kind of green alga); and by tangled forests of mangrove roots.

Mangroves living close to the tidal channel are often colonized, below the water line, by strikingly coloured sponges. Their blue,

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purple, and orange colours provide an indication of their different kinds of microbial guest, and they are especially fond of nurturing blue-green microbes called cyanobacteria. In terms of shape, some of the sponges on the mangrove roots look like golf balls, while others resemble flower vases and even church organ pipes. The animal nature of the sponge group, properly called the Porifera, was for long debated because they can look and behave a bit like plants. Unlike the corals, for example, sponges have no gut or nerve network. They do not recoil when attacked by fish. Being little more than a colony of cells, sponges can also take almost any shape and will grow in any almost direction. But they are far from passive. In one infamous experiment conducted in the early 1900s, a living sponge was disaggregated by squeezing it through the very fine mesh of a lady's silk stocking—presumably with her permission, and hopefully when she was no longer wearing it. The sponge cells seemed quite unperturbed and were able to 'pull themselves together' on the other side of the silk stocking. (This experiment is not something to be tried at home on an earthworm, or even on a jellyfish, because the outcome would be unpleasant.) In other words, they behave much more like a colony of cells than do the cells of a jellyfish or the cells in our own bodies. I have even observed sponge colonies creeping about, by means of cellular migration, at a rate of a few millimetres a day. They can also put out long streamers of cellular tissue, either to colonize new areas or to kill unwanted neighbours. This they do, like Nero's mother, by means of slow-acting poisons. Perhaps the strangest feature of living sponges is that they have little regard for body symmetry, with inhalant and exhalant openings scattered willy-nilly over their surface. This lack of symmetry in sponges is usually regarded as a primitive feature. It contrasts sharply with the beautiful symmetry of creatures that

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occupy the next rung on the ladder of life, such as the jellyfish and the corals.

Even so, the body wall of a sponge has great beauty, as is perhaps familiar if you ever take a bath. Careful inspection shows that it is full of tiny holes through which the seawater is drawn by thousands of little cells. These choanocytes will typically wave their tiny whip-like flagella in the manner of cheery supporters at a football match, causing a one-way flow of sea water from the outside inwards. But so tiny are the pores through which this water must travel that they are unsuited for filtering anything much bigger than a bacterium in size—about a thousandth of a millimetre across. Particles larger than a few thousandths of a millimetre across will tend to clog the pores, with fatal effect. We chordates can cough and sweat, but sponges have no body mechanism for cleaning their clogged pores. In such a dangerous situation, sponges are faced with two options. The first is simple: to remain in areas of water provided with laminar flow, not turbulent flow, and with good water clarity. This is what confines many modern sponges to the deep sea floor. The second is more subtle: they hire a cleaning service such as that provided, quite willingly, by invertebrates such as shrimps and brittle stars. This is how many sponges are thought to cope with detritus in the reefs and lagoons of Barbuda.

There is one more organism that we need to take a look at here. Vivid green in colour, it forms great clumps along the floor of the channel and flourishes in mangrove-enclosed ponds. Wherever it thrives, the seafloor is covered with something that looks a bit like snow-white cornflakes. Indeed, it is these 'cornflakes' of chalky material that make up much of the seafloor here, and in parts of the coral reef as well. When one of these green clumps is brought to the surface, we can see that it looks like a tiny Prickly Pear

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Cactus. There are, however, neither specialized tissues nor flowers because it is really a kind of alga in which the photosynthetic pigments and nuclei float around wantonly within a very large cell—called a syncytium. Interestingly, this creature, named *Halimeda*, shows us one of the ways in which higher, multicellular organisms could have evolved: by the subdivision of this syncytium into cells. But there is more. A snorkel around the lagoons in the cover of darkness shows that *Halimeda* changes colour at night, bleaching to a bone white colour. That is because the green photosynthetic pigments have sneaked away from the surface of the seaweed, to lie protected within little canals inside the calcareous ‘cornflakes’. It does this every night, as though trying to protect its valuable photosynthetic pigments from the grazers of darkness that haunt the lagoon floor—sea urchins, snails, and fish. These grazers of darkness come out from their hiding places as soon as the barracuda and other daytime predators have gone to sleep in the mangrove. In other words, the chalky ‘cornflakes’ of *Halimeda* are a deterrent to grazers. In an earlier world without grazers and predators—such as Darwin’s Lost World perhaps—these cornflakes may not have been needed.

Up Cuffy Creek

From these mangrove swamps, it is but a short swim towards the more restricted lagoons and saltponds or creeks, where the balmy waters are usually rather shallow, and often less than knee-deep. Wading barefoot across the creek floor, the soft mud can prove distinctly ticklish as it squirms between the toes. A faintly sulphurous aroma, a bit like that from boiled spinach at dinner time on *HMS Fawn*, also wafts up from the mud here. That is because these muds are rich in organic matter, interestingly like the old

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lagoons we shall later meet that yield the first signs of animal life. The salty waters of Cuffy Creek quickly tell where the deepest skin scratches are, too. Neither corals nor seagrass can withstand the stresses here. In these restricted creeks, the habitable niches for animals are in rather short supply.

The floors of these creeks are covered with a natural fabric that rather resembles a low quality Persian rug, all woven together using pastel-coloured silky filaments (see Plate 2). These threads are, however, embedded within large amounts of snot-like muci-lage, a feature rarely met with in Persian rugs, even the very cheapest ones. This slimy rug is called a 'microbial mat' or a 'biofilm' by biologists because of the dominance of cyanobacteria and other kinds of filamentous microbes. To a geologist, such a rug is known as a 'stromatolite'—meaning a layered or bedded stone. Ancient examples can be cabbage-like, and may preserve the remains of the earliest known communities. But here, in Barbuda, these living 'stromatolites' are grazed flat by high-spired snails such as *Batillaria*. This is a tough little mollusc that will feed happily until the dry season comes, when it will seal off its aperture and snooze for a while. Snail shells provide a lifeline for other creatures too. Fronds of the bottle-brush alga, *Batophora*, little more than a centimetre long, attach to shells here because there is little else to cling on to. And, in turn, the high surface area of each little bottle-brush alga provides a niche for thousands of tiny protozoans, foraminifera with the delightful name of *Quinqueloculina*, meaning 'a dwelling with five tiny chambers'.

Even these havens are obliged to give way to a monotonous carpet of microbial mats in the hottest and saltiest ponds. Water here, if present at all, is rapidly soaked up beneath the mat. Walking across the rubbery surface, a well-placed footprint will

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often penetrate some centimetres below the surface to reveal, within the mat, striking bands of different colours. This zonation shows that microbial life survives in the salt ponds by diving down into the darkness. Winning microbes keep themselves aloof in the top zone while the losers become progressively stratified downwards through the sediment, forming a hierarchy that is seemingly stricter than humans in a Caribbean holiday resort. Sun-worshipping cyanobacteria such as *Oscillatoria* are like superstars that wish to be seen thriving in all the best lit spots. Beneath them lies a thin layer of microbes that has turned beetroot red, because of the presence of a sulphur bacterium called *Thiocapsa*, which has purple photosynthetic pigments. They cannot tolerate oxygen.

The rest of the 'layer cake' looks and smells a bit like a rubbish tip. This whiff of rotten eggs betrays the presence of a sulphate-reducing bacterium called *Desulfovibrio*. Feeding slowly on organic matter in the sediment, these microbes produce hydrogen sulphide as a toxic by-product that, happily, also helps keep unwanted competition away. Sulphate-reducing microbes are like the lowlife in a downtown nightclub—they can bear neither light nor oxygen.

Within a mere finger's breadth beneath the surface of the mat, we have therefore seen a transit from 'oxygen heaven to anoxic hell'. These changes have largely been brought about by those kinds of 'primitive' microbe that scientists call prokaryotes. Prokaryotes are primitive because their chromosomes are not held together in a nucleus, but drift about wantonly in the cell. Not only that, but they also lack those other useful gadgets that tend to be found in a true eukaryote cell. In this respect, we might say that eukaryote cells are like the Swiss Army Knives of the cellular world—they come provided for almost every eventuality, having chloroplasts for photosynthesis, mitochondria for energy storage,

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and cilia for locomotion. Prokaryotes have none of these 'gadgets'. But they make up for this lack of gadgetry by their stupendous ability to grow rapidly when the conditions are right. And conditions are nearly always right for at least one kind of prokaryote to flourish. Though seldom more than one-thousandth of a millimetre across, prokaryotes are truly the rulers of the world. They get everywhere. Without them, our lives would be seriously less amusing. We would probably starve to death before we suffocated, but it would be a close call.

The Great Chain of Being

One day on Barbuda, I amused myself by arranging seashells and flotsam along a tide strand into something like the Great Chain of Being. Pieces of microbial mat, with smelly bacteria and cyanobacteria were made to form the base of the chain; all of these were prokaryotes—single celled and without a nucleus. Above these on the beach I laid out a handful of ruby red *Homotrema* shells—to stand for single-celled protozoans with cell organelles like a nucleus. Higher along the chain were placed some yellow sponges—with no real symmetry and no organs—and then some white pieces of coral, to stand for cnidarians with organs but neither blood vessels, nor kidneys, nor brains. Above these were arranged such examples of the major animal groups as I could muster: a star fish (for echinoderms), a worm tube (for annelids), a pink Queen Conch shell (for molluscs), a land crab (for arthropods), and a seabird (for our own phylum, the chordates).

Something like this almost feudal ranking of living creatures—from sponges to humans at least—has been known and remarked upon by philosophers and writers on medicine for millennia. Going back to the archetypes of the Greek philosopher Aristotle

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(384–322 BC), this Great Chain of Being was becoming central to thinking about the natural world by the mid to late 1700s. But the wider evolutionary significance of this spectrum in living organisms was not widely discussed in public during the Christian era, until the chance of being burned alive in the market place began to recede. Emboldened by the Enlightenment of the eighteenth century, Erasmus Darwin—the illustrious grandfather of Charles Darwin—felt it was safe to write the following big and beautiful thought in his treatise called *Zoonomia*, published as early as 1794:

Would it be too bold to imagine, that in the great length of time since the earth began to exist, perhaps millions of ages before the commencement of the history of mankind, would it be too bold to imagine, that all warm-blooded animals had arisen from one living filament, which the first great cause endowed with animality, with the power of acquiring new parts, attended with new propensities, directed by irritations, sensations, volitions, and associations; and thus possessing the faculty of continuing to improve by its own inherent activity, and of delivering down these improvements by generation to its posterity, world without end?²³

Had either Baron Cuvier of France, or Richard Owen, ever been served up a banquet of things to eat—ranging from microbes to birds—during the early nineteenth century, they would have thought each organism in the menu had been created by a master chef—the creator God—who seldom made more than slight variations upon the standard recipe.²⁴ If both shrimps and lobsters had been on the menu, these would have been seen as little more than variations upon the basic theme of a ‘crustacean archetype’. Likewise for echinoderms, molluscs, and so forth. Each of these was centred on an ideal body plan—an archetype—and there seemed no prospect of any intermediates between them.²⁵

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But in 1809, Jean Baptiste Lamarck, then the lowly-sounding ‘Keeper of Insects, Shells, and Worms’ at the *Musée d’Histoire Naturelle* in Paris, was starting to explore a much more radical idea—that the Great Chain of Being was more like lunchtime in a works canteen, where people had sat down at different times to eat their way through a *set menu*.²⁶ Some animal groups had made an early start on the menu, beginning long ago as simple cells, and some of these had now reached the final course, with highly developed brains (such as ourselves). But the dinner gong for each animal lineage had been different, and many organisms, such as shrimps and squid, had only just reached the middle of the menu. Many more had made an even later start, and were not yet far past the *primaeval* soup stage. It was evolution but not as we know it.

There was a problem, however, with this idea about life and its evolution. As Richard Owen was later to point out, higher animals such as fish and ourselves do not go through *all* the stages of lower animal kingdom during their embryonic development from egg to adult.²⁷ No human child, for example, goes through the stage of being a mollusc. Instead, it seems that each member of an animal phylum starts out with a *set menu* (the embryo) that becomes increasingly *a la carte* as the individual grows and matures. In pointing out this phenomenon of divergence from the *set menu* during growth, Owen was actually pointing the way towards the explanatory power of the Great Tree of Life, as later revealed by Charles Darwin in 1859.

For Darwin, this pattern of branching was to be found at all levels, from the genealogy of individuals to the divergence of species and even to the divergence of the animal groups—the animal phyla themselves. As we have seen, though, Charles Darwin was presented with a surprise in the fossil record: all the major animal groups seemed to appear rather abruptly and fully formed.

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While trying to understand the Origin of Species, he found himself confronted with the Origin of Animal Phyla, an altogether bigger puzzle. According to his understanding at that time, those missing animal ancestors should have taken a very long time to diverge from their single ancestor. And they should have left behind them a few intermediates between the animal phyla—missing links—in the fossil record. But not a trace of those ancestors or intermediates had been found below the Cambrian by 1859.

A molecular puzzle

It took about a century of research following Darwin's great book of 1859 before the magnitude of the jump from prokaryotes (such as cyanobacteria) to eukaryotes (such as *Homotrema* and ourselves) could be starkly revealed as the biggest dividing line in the whole of life. But in another twenty years, another revolution was about to take place, following the discovery of DNA and RNA sequencing techniques. Molecular sequencing of the living world has latterly changed our perspective on the Great Tree of Life in two ways that are important for our story. First, it has shown us that prokaryotic cells are vastly more diverse than can be told from their shape or size alone. A teaspoon full of forest soil, for example, can contain up to five thousand different kinds. All of them can, however, be divided into one of two main types: Eubacteria, or 'true Bacteria', like the cyanobacterial mats of Cuffy Creek. And Archaea, like the methane producers found in our own guts. According to these molecular studies, we may share more in common with the Archaea than with the Eubacteria. If so, it is from whiffy Archaea that our own ancestors are widely thought to have evolved.²⁸ A second important finding shows that all the animal groups, from sponges to fish and ourselves, cluster very close together near the crown of the Tree.²⁹

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There are, however, many things which molecular sequencing cannot yet tell us about evolution. Molecules cannot tell us much about creatures that have never been studied—either because they are no longer alive, or because they have not yet been discovered. Our best hope of seeing these lost worlds is, in the view of myself and many colleagues, the fossil record itself. Nor can molecules yet tell us anything reliable about rates of change in evolution. The principle of the molecular tree is simple. It notes that differences in the genetic code accumulate with time, and that these similarities and differences can be measured and used to reconstruct the Great Tree of Life. Sampled in this way, living organisms can only form the tip of a branch on the Great Tree. But the similarities between them can be used to infer, without seeing them, links between the branches that lie beneath the canopy.

The idea of a molecular clock builds upon this molecular tree. It assumes that the greater the number of differences in a given piece of code in two descendants, the longer the time since they diverged in geological time. And it says that, if we can be confident about the approximate rate at which mutations occur, we can then estimate how long ago two living branches diverged in the tree of life. Molecular clocks are a neat idea, and they have provided some interesting insights into relatively recent periods in the history of life. But molecular clocks are themselves utterly dependent upon fossils to calibrate their time scales. It is important to accept that there has been much misunderstanding about all of this. These clocks compare the rates of gene substitution along a given string of genetic code through time, calibrating it against various well-known fossils from the rock record. Backward projections from the earliest known fossil examples and into 'Darwin's Lost World' must therefore enter into a dark age filled with uncertainty. Unhappily for molecular biology, it is now clear that

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rates of substitution can vary widely—between creatures that live long or die soon, or between populations that are large or small, and so forth. And geology has shown that populations before the Cambrian explosion are likely to have changed dramatically in ways we could never have anticipated until recently, as we shall see.

To comprehend the problem with molecular clocks, imagine that you are looking at a murder scene. The Palaeontological Police have found a body beneath a railway line. And the Molecular Horologist has been asked to calculate the date of the victim's birth, by *using a current railway timetable*, even though the crime took place long before the track was laid down. But no English judge would likely admit such evidence into a court of law.³⁰ Regrettably, therefore, molecular clocks cannot yet be admitted into our own court as evidence for dating the origin of animals. Only animal fossils themselves will do. When there are no animal fossils in the rocks, then the clocks can be no better than their assumptions. And assumptions, as we shall see, can sometimes be bigger than the things they seek to explain.

A wrong question

This brings us to a puzzling question. Can living organisms, like those in Barbuda, provide us with the keys to Darwin's Lost World? Consider, for example, the microbial mats of Barbuda, with their cyanobacterial mats thriving at the surface and their smelly sulphate-reducers at depth. Could such ecosystems preserve something of an ancient world from, say, a time before the evolution of grazing animals and atmospheric oxygen? Or consider the popular notion that sponges and cnidarians, like those we have met in the reefs and lagoons, resemble the ancestors of 'higher

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animals' including ourselves. Shouldn't we be looking for them in the rocks before the Cambrian?

My case here is that these living creatures are not likely to provide the answer to our big question. That is because they provide an answer to the *wrong question*: 'what do the simplest animals look like today?' rather than: 'what did the simplest animals look like way-back in time?' We can now see, for example, that there is a remarkable degree of connectedness between modern creatures. Oxygen from 'higher' plants is needed to make the sulphate on which sulphate-reducing bacteria depend. Climbing further up the Great Tree of Life, we see that many protozoans depend upon things that branch even higher—things like corals and snails or seagrass. On the next branch, we find that sponges can be peculiarly dependent upon the cleaning service provided by 'higher' animals like brittle stars. And they need more complex animals to stir up the microbes on which they feed. Sponges are therefore highly adapted to the world of worms, shrimps and brittle stars. The same caution can be applied to the idea that early oceans should have swarmed with jellyfish. Such animals are, today, provided with specialised stinging cells-called cnidocytes, as well as with suprisingly complex eyes. But these seem best equipped to capture animals that lie 'higher' on the tree of life. In a world without worms and shrimps, would jellyfish have had any use for such stinging cells? It seems to me doubtful.

All organisms of supposedly lowly status, like protozoans, sponges, and corals, now seem to be hugely dependent upon a world tuned to the presence of higher beings, from molds to molluscs, and now us. Before the Cambrian, the pattern of life of these simpler creatures may have worked in markedly different ways. In Baron Cuvier's Chain of Being every creature was believed created by God and given a particular status. Those

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species remained static through time until they were intentionally snuffed out. Moving forward to Darwin's Tree of Life, however, the modern biosphere is seen by us as the branching tips of a great tree, arising from organic evolution over several billions of years. Darwinian evolution has required a lot of physical change within some lineages, such as vertebrates, while others have seemingly experienced physical change to a much lesser extent, such as cyanobacteria. But while simpler organisms may appear to resemble their ancestors more than complex ones, all have evolved to fit in with the complex ecology of the modern world.

In other words, we must not expect to translate our modern world and its biology far backwards in time. Life in the early biosphere was probably very different from anything we see today. The world before the Cambrian may have been more like a distant planet. This is the mystery I here call Darwin's Lost World. And its clues lie sleeping in the fossil record.

Oddities in time

During October of 1970, with hammer in hand, I circled the island of Barbuda, somewhat shakily perched on the back of a nag, in search of rocky outcrops that might help to answer this deeper question: *just how good is the fossil record?* I then discovered something rather curious: that the ancient biological communities of Barbuda—microbial mats and seagrass, mangrove and reef—were all selectively preserved in rocks just a few tens of metres inland from their modern counterparts. In fact, the older the fossils, the higher they were found to lie on such benches above sea level.

Closer examination of the cliffs around Barbuda also showed another intriguing pattern, that strong filters act—both for and

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against—the entry of dead organisms into the fossil record. Shelly fossils made of a chalky material called calcite had the highest chance of preservation. Under the microscope, I could therefore see the remains of calcareous algae, foraminiferid tests, oysters, and the ossicles of sea urchins, all of them made of calcite. In rocks dating to the last interglacial, which lie about 6 metres above present sea level—and are some 125,000 years old—molluscs and corals could be preserved but their metastable aragonite shells were often full of holes. In the higher and older rock benches, up to a million years old, such fragile shells were dissolved or replaced. It was no surprise, therefore, to find that even more delicate soft tissues, such as leaves, roots, tendons and muscles were seldom preserved at all. Even so, a few small windows could be used to look upon their story. Seagrass communities, for example, had left behind ghostly signals in the fossilized shelly biota.³¹ And, in rare instances, even mangrove leaves and seagrass roots could be found buried within peaty clays deep beneath the lagoon. In other words, evidence could be seen for a natural spectrum in ‘fossilization potential’, ranging from *common* for the skeletons of echinoderms and foraminifera on the one hand, to *rare* for animal tissues and flowering plants on the other. Now Charles Darwin had predicted something a little like this back in 1859 when he wrote: ‘No organism wholly soft can be preserved.’ Though as we shall discover later, this prediction would prove somewhat wide of the mark for an Earth before the evolution of animals.

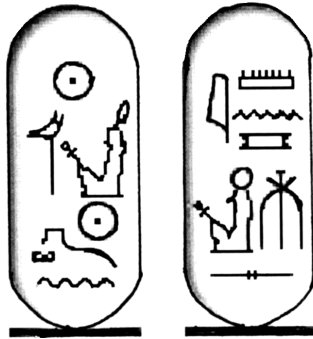
Encrypted in stone

How real, then, was the Cambrian Explosion? To answer this and similar puzzles, we need to try to decode the early fossil record. But, as we shall see, some claims for cracking this 4-billion-year-long

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code have recently proved to be false readings, while others show great leaps of intellectual grandeur, on a par with Champollion's decipherment of the Rosetta Stone. Strange fossils do indeed share many daunting similarities with lost languages such as Egyptian hieroglyphs. Both are preserved as arcane geometries—strange markings, glyphs, in rock—and both largely conceal their deeper meaning from us. Both are also capable of false translation. In the case of hieroglyphs, we need only remember one haunting reading conjured up by the romantic poet Percy Bysshe Shelley back in 1817, from a colossal statue of Rameses II, preserved along the Nile near Luxor

And on the pedestal the words appear:
 'My name is Ozymandias, King of Kings:
 Look on my works ye Mighty and despair!'
 Nothing beside remains. Round the decay
 Of that colossal wreck, boundless and bare,
 The lone and level sands stretch far away.



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Shelley's reading is stirring and justly famous. But Shelley was not Champollion. No such words are actually present on the great statue. Decoding of the actual hieroglyphs of a cartouche on a nearby wall was impossible until Champollion got to work in 1822. This cartouche actually says 'User Maat Ra, Setep en Ra', which was the throne name of Rameses II (1293-1185 BC). It means 'The Justice of Ra is Powerful, Chosen of Ra.' Nothing about 'Ozymandias' here, nor about 'despair'. Shelley's reading was poetic, but it was sadly false.

To read the fossil runes correctly, it is necessary to adopt the mentality and techniques of the code breaker and the spy. First, we need to carefully record and decode the patterns. And then the patterns must be interpreted in terms of process. For example, deciphered hieroglyphs have allowed us to understand the challenges faced by past civilizations—of famine, flood and invasion. And they allow us to glimpse lost worlds.

But this translation from pattern (fossil) into process (the organism and its biology) also requires the skills of a poker player. Imagine that we have sat down with three other explorers, say at the Luxor Hotel, where Howard Carter once dined, to play a game of cards, for access to our hidden treasure, the early fossil record. We know that we will need to win the game to survive. But the other players are not only poker-faced, they are downright mute. Worse—we are not told what game we are playing! Consider, for example, being given a hand of seven cards, ranging from Ace to King. Except that we don't know whether the Ace card is high or low, or whether spades trump hearts. Or whether there is a joker or not.

As soon as we are told the name of the game, or its rules, then all becomes clear and the game can be won. But we are never told what the rules are with the fossil record. We must therefore take

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risks—like a poker player—and begin by guessing at the rules. Then, step by step, we can hopefully iterate our game towards a fuller understanding of how to win. That is, to some extent, how decoding of a hidden message typically works. But remember this: explorers have only been sitting down at the green baize table of science, trying to decode the game of life, for about four hundred years or so. Yet four hundred years is a mere blink of an eye within the six million years of our existence as upright apes. Winning the game of decoding the early fossil record is also bound to be difficult in the first few rounds. As we shall see, it had to evolve from careful and prolonged watching for patterns on the one hand, towards inspirational hunches (that we call 'hypotheses') about processes on the other. Human progress towards learning the rules for decoding the fossil record has therefore been slow, requiring trial and error, with lots of questions, intuition and counter-intuition, accompanied by oceans of doubt. But then, science, which always rejoices in a good question, is a unique system for the measurement of doubt.