

Prologue

The water felt chilly as I waded out to fetch the battered skiff from its mooring. It slid easily over the glassy lagoon to the beach where Julie waited with our diving gear. We had been married a month and, in lieu of a honeymoon, I had persuaded her to accept two months of fieldwork studying fish behaviour on this remote patch of Australia's Great Barrier Reef. It was June 1987, winter in Australia and summer back home. Two herons picked their way along the shoreline looking for breakfast. They flapped off as the outboard engine coughed to life and we set course for a spot a mile away across a maze of coral so complex that it would have baffled the most capable navigator.

We anchored on a rubble ridge that separated the lagoon from the open sea. This was our first ocean dive here and the thrill of expectation was tempered by a frisson of fear. Ahead of us, the homely greens and browns of the shallow reef gave way to the dark indigo of the deep. Huge buttresses of coral plunged down hundreds of feet in parallel walls separated by deep channels. Vivid purple finger corals vied for space with yellow lettuce-coral, while great mounds of blue and green polyps rose from the bottom.

The reef was a confusing swirl of movement, like Grand Central Station at rush hour. Stocky surgeonfish with electric-blue stripes raced around purposefully while loose groups of gaudy parrotfish dodged them. Clouds of damselfish and anthias hovered above, delicately plucking invisible food from the water. Along the edge of the reef I counted eight loggerhead turtles, one for each buttress in view. A grey reef shark headed our way, but barely acknowledged us as he passed by. The whole scene felt timeless and primordial. I was transfixed.

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I wonder what I would have thought if, on our return to shore, we had been greeted by a curmudgeonly sage who prophesied that in one hundred years this magnificent reef would be a crumbling ruin, that its bright coral escarpments would be replaced by green fuzz, and the ranks of fish would have thinned and given way to swarms of jellyfish and gelatinous plankton. I would probably have thought him mad. Nothing could have seemed less likely. And yet, less than twenty-five years later, most serious marine scientists predict just such a fate. We can already see it happening.

Eleven years after our honeymoon dive, in a foretaste of a warmer world to come, the oceans heated so dramatically that a quarter of the world's coral died. In much of the Indian Ocean, between 70 and 90 per cent of all corals died, taking with them countless creatures that used coral for living space or food. If three-quarters of our forests had withered and died that year, people would have demanded to know why and aggressive plans would have been drawn up for their recovery. Yet outside the world of marine science, this global catastrophe passed largely unseen and unremarked.

For most of civilized history, the world's oceans have been very stable. Since the seas levelled off six or seven thousand years ago, after the last ice age, they have for the most part been predictable. Yes, coasts have retreated and advanced under the relentless influence of wave and tide, but the oceans themselves seemed changeless. Their constancy contrasted with the world above water, where landscapes underwent dramatic alterations as first pastoralists and agriculture spread, and then later cities and industry. Today it is the turn of the oceans.

This is a book about the sea change unfolding around our planet. In the last half century human dominion over nature has finally reached the oceans. The speed and extent of these changes has caught us unprepared. The sea is becoming more hostile to life, and not just for the creatures that swim, scuttle or crawl beneath the waves but for us too. Only in the last decade or so have we begun to recognize how our activities are reshaping the oceans, and what that means for our own well-being.

We have long known how humankind has changed the land, modifying landscapes to suit our needs and affecting its wildlife across

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thousands of years – tens of thousands of years if you consider how Australian Aboriginals and Native Americans used fire to clear vegetation and facilitate hunting and gathering. But we persist in believing, as Lord Byron put it, that humanity's dominion stops at the sea. Yet, even in Byron's time human impacts on the sea were significant. The great auk stood two decades from extinction, and the Atlantic grey whale had vanished for ever. Fishing had begun to deplete stocks close to coasts and to damage habitats with trawls and dredges. People were building coastal defences and large areas of marsh and estuary had been reclaimed for ports and agriculture. In populous regions, rivers filled coastal estuaries and bays with mud washed from land exposed by the plough.

Our influence has grown exponentially since then. The last two hundred years have seen marine habitats wiped out or transformed beyond recognition. And with an ever-accelerating tide of human impact, the oceans have changed more in the last thirty years than in all of human history before. In most places, the oceans have lost upwards of 75 per cent of their megafauna – large animals such as whales, dolphins, sharks, rays and turtles – as fishing and hunting has spread in waves across the face of the planet. For some species, numbers are down as much as 99 per cent, as is the case for the oceanic whitetip sharks of the high seas, American sawfishes and the 'common' skate of Northern Europe. By the end of the twentieth century, almost nowhere shallower than a kilometre remained untouched by commercial fishing, and some places are now fished to three kilometres down.

For thousands of years the oceans have been our conduit for commerce. Today they are the highways of a globalized world and the roar of engines can be heard in every corner of the sea, even beneath polar ice. Increasingly, they also provide us with oil and gas and growing scarcity has driven us to venture deeper and further offshore. We are within a decade or so of the onset of deep sea mining. Riches beckon in the blackness of the abyss, thousands of metres down. Dark nuggets of precious metals and rare earths lie scattered over the ocean bottom, seamounts are crusted in cobalt, and deposits of gold, silver and manganese spewed forth from superheated springs are nearly within reach of the miners.

Why, in the face of widespread evidence of human impact, do so

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many people persist in thinking that the oceans remain wild and beyond our influence? The answer lies in part in the creeping rate of change. Each generation forms its own view of the state of the environment. Younger people generally fail to perceive changes experienced by the elderly, and so knowledge of past conditions fades with time. Younger generations are often dismissive of the tales of old-timers, rejecting their stories in favour of things they have experienced themselves. The result is a phenomenon known as ‘shifting baseline syndrome’, as we take for granted things that two generations ago would have seemed inconceivable.

Loren McClenachan unearthed a telling example of shifting baselines in the archives of the Monroe County Library in Florida when she was doing research there as a graduate at Scripps Institution of Oceanography.¹ She found a series of photographs of catches of fish landed into Key West by one recreational fishing charter company between the 1950s and the 1980s. She extended the series into the twenty-first century with her own pictures taken at the same dock. In the 1950s, huge Goliath groupers and sharks dominated catches, many of them bigger and fatter than the anglers. As the years pass by, the fish shrink and groupers and sharks give way to smaller snappers and grunts. But the grins on the anglers’ faces are just as broad today as they were in the 1950s. Modern-day tourists have no idea that anything has changed.

The oceans are changing faster than at almost any time in Earth’s history and we are the agents of that transformation. Many of these changes will test the ability of its denizens to survive into the future. These alterations are also reshaping our own relationship with the sea and threaten many of the things that we most cherish and take for granted. Our failure to notice creeping environmental degradation has compromised more than our quality of life. In extreme circumstances it threatens human welfare. History offers many examples of civilizations that have been destroyed by environmental catastrophes that they have unwittingly brought on themselves. Easter Islanders cut down all their homeland’s trees to raise statues to their gods and then starved when their soil dried up. Mesopotamians invented sophisticated irrigation agriculture, but the technique eventually left fields so salty they could no longer grow crops. Mayan hill-slope

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farming practices stripped the region of its topsoil, precipitating the collapse of this extraordinary civilization during prolonged drought. In these and many similar cases, adverse effects were local to an island or region. Today, our influences are global, and we will have to act globally to reverse the impact of what we have already done.

I began my career studying coral reef fish. From the moment I first dived a Red Sea reef, I was hooked (my wife, Julie, was similarly hooked by our honeymoon trip to the Great Barrier Reef and also became a marine biologist). Thirty years on, fish are still at the heart of my research but my outlook has expanded to a much wider interest in the relations between people and the sea over the course of history. Nonetheless, when I began the research for this book there were huge stretches of ocean science of which I was only dimly aware. Scientists are specialists and devote their lives to research within narrow fields that become further constricted as time passes. Each pores over a fragment of the world, turning it over and over in his or her mind like a chip of some mosaic. Management of pollution is segregated from that of fisheries, which in turn are rarely considered in the same place as shipping or climate change. This means that impacts are discussed in isolation at different meetings and by different people who never quite see the overall picture. I decided to write this book because I felt there was an urgent need to bring all these separate fiefdoms together. What I found along the way has been a revelation.

We fear change and resist it. Perhaps that resistance is hardwired into our genes: the familiar seems safer than the unknown. Many animals go to strenuous lengths to return to the place where they were born to breed, probably because past success there gives greater assurance of future success. This is a dynamic world and change sometimes brings good things, but some changes, notably those which erode our planet's resilience, are harmful, for when resilience is worn away all bets are off for the future. The path we are on today, as I will show, is pushing ocean ecosystems to the edge of viability. Heedless of consequences, we are emptying the seas of fish and filling them with pollution, and our unplanned experiment with greenhouse gases is gradually infiltrating the deep sea.

Although a few of the human influences that I will describe in this book have been underway for centuries, others have really only taken

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hold in the last fifty years. In this sense, our impacts on the oceans have been sudden – instantaneous almost – given that they have occurred in less than one-thousandth of the 150,000 years or so during which modern humans have existed. The response demanded to counter these impacts will also have to be sudden and global in scale. Few people yet grasp the gravity of our predicament.

In this book I will take you on a voyage beneath the waves to reveal the seas as few know them. I will show how human activities have for centuries been unpicking the fabric of marine life. Until recently we have been able to ignore much of the harm done by our heedless use of the sea. But, as the scale and intensity of human influence have grown, the rate of change has accelerated and we must now confront the consequences.

To understand the present we must first know the past. I begin at the beginning, when the world began, before picking up our own story when humankind first makes its appearance on Earth. For tens of thousands of years, our only real impact on the oceans was to remove fish and shellfish, so I start with a brief history of hunting and fishing and how they have evolved through time. The industrial revolution heralded the emergence of people as agents of planetary change, and I move on to describe how the use of fossil fuels, and their impact on currents and climate, is transforming the sea in ways not seen for hundreds of thousands or even millions of years. Sea levels are rising faster than the highest rates predicted only twenty years ago. They now threaten dozens of the world's great metropolises, and within fifty years could inundate vast tracts of our best agricultural land, imperilling food security. In one of the least known but potentially most damaging effects of greenhouse gas emissions, within the seas themselves acidity is going up in step with carbon dioxide. The outcome could be catastrophic. Shell-forming animals, including many that sustain ocean food webs, and thereby our own fisheries, will find their lives increasingly difficult. Not for 55 million years has there been oceanic disruption of comparable severity to the calamity that lies just a hundred years ahead if we fail to curtail emissions fast.

By absorbing heat the oceans have so far spared us from the worst of global warming. But warming seas have set life on the move, so in

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the years to come the fortunes of some fishing nations will wane as others rise. But warming will have far more grave effects on marine productivity, driving it to excess in some places while turning others into oceanic deserts. If climate change and fishing were our only threats to life in the sea, matters would be bad enough. But ocean life faces other pressures, like pollution. I survey pollution effects ranging from toxic chemicals and the now ubiquitous plastic, to sewage and fertilizers and less familiar pollutants like noise and invasive species. Pollution problems have grown in severity with time, so much so that in many regions we see the emergence and spread of dead zones as oxygen is sucked from the water by decaying plankton. The cocktail of human stresses is mixed differently from place to place, but the result is the same: their effects in combination are far worse than in isolation. We are transforming life in the sea, and with it we are undermining our own existence.

This book is not a catalogue of unavoidable disasters ahead. There is much we can do to change course, if we take the opportunity now. But time is of the essence. The longer we ignore problems or prevaricate, the less leeway we have to avoid the direst of our possible futures. I devote the rest of the book to how we can plot a new course to safeguard the oceans and ourselves. What we need, I will argue, is an ambitious plan to reverse long-term trends of depletion and degradation, to recapitalize the value of the oceans to people and wildlife, and to improve the quality of everyone's lives, especially of generations yet to come. We don't have to look on helpless as all that we love about the sea is sullied. Change for good is within our reach.

I

Four and a Half Billion Years

In a remote part of Western Australia there is a range of hills so smoothed by time that little more than undulations are left. Summer sun bakes the red earth and sparse trees dig deep to quench their thirst. Close up, jumbled slabs reveal beds of smoothed pebbles brought here by ancient floods – very ancient, for the Jack Hills rocks were laid down 3 billion years ago. This landlocked desert may seem like a strange place to begin a book about the oceans, but, as unremarkable as they appear, these stones have rewritten the earliest history of our planet.

Zircons are pyramid-shaped crystals that coalesce from cooling magma. They are incredibly resilient and survive through repeated re-melting and hardening as the crust of our restless planet is recycled by plate-tectonic movements. Zircons form gems of many hues. The name is thought to come from the Persian *zargun*, which means golden, probably in reference to the translucent yellow stones that were once traded through Persia from Sri Lanka to Europe and China. Brilliant sky-blue crystals were mined from river mud by the people who built the temple city of Angkor Wat in Cambodia.

Jack Hills' zircons are less showy. In fact they are so small they can hardly be seen with the naked eye. It took over 200 pounds of Jack Hills rock to yield less than a thimbleful of zircons.¹ But it was worth the effort. Each crystal was found to contain traces of uranium that decays over time into lead, making it a geological chronometer that ticks away the eons. By measuring the ratio of uranium to lead, you can date the time of crystal formation to within a few tens of millions of years. The most ancient Jack Hills crystal is 4.4 billion years old, which takes us to within a whisker of the formation of Earth (well, a

170-million-year whisker, but that is close!). It lets us glimpse a planet in its infancy.

We can never be sure of all the details of Earth's birth and childhood; no one was there to see it, and we can't rewind time to have a look. The best we can do is to search the world for ancient rocks and fossils and probe them for their secrets. We spin theories that fit the evidence and rework them when new data find them wanting. These days, new ways of interrogating the past are developed with breathtaking speed, so the picture is coming into clearer focus. Although many uncertainties remain in the story I will tell in this chapter, the broad pattern of events is well established. About 4.57 billion years ago, the Earth coalesced from the rotating disc of dust and debris that would become our solar system.² The sun is around the same age, so our planet formed when the match was struck to light the solar system. As debris pounded the growing planet into shape it grew hotter until the rocks melted. Seen from the darkness of space, our world would have glowed like a faint sun. Sometime around 4.53 billion years ago, a planet the size of Mars barrelled into this new world and smashed off pieces that became the moon. The impact was so enormous it vaporized rock, and the primeval world was shrouded by a thick atmosphere of this vaporized rock and other gases. As the planet cooled, a time came when minerals condensed, and for 2,000 years the skies rained molten rock onto an ocean of magma below. Even after this thousand degree deluge ended, the atmosphere remained thick with vapour and gases, and atmospheric pressure at the surface of the flaming sea would have been hundreds of times higher than today.³

We owe a lot to this collision. It knocked Earth's axis of rotation askew, which gives us seasons.⁴ Over the vast plain of geological time, the moon has slowed and stabilized the Earth's rotation, giving us longer days. A billion years ago, a day was just 18 hours and the year lasted 480 days. Early on, the moon was much closer to Earth and would have loomed large in the sky. The moon's gravitational pull gives us much greater tides than the more distant sun alone and the flood and ebb of tides would have been violent as they rose higher and fell faster in the short days.⁵

The searing heat of fireball Earth is called the Hadean. For a long

time, we thought these hellish conditions lasted for the first half billion years of Earth history, but a zircon from Jack Hills has recently transformed that view. The 4.4-billion-year-old crystal and tiny particles of other materials trapped within it formed at temperatures characteristic of coalescing granite in contact with liquid water.⁶ The continents are built from granite, so we can see within this insignificant speck the imprint of a cooler world with land and water long before such a place was suspected to exist. Instead of seething oceans of fire, the world might have been more like a steamy sauna.

The Earth is unique within the solar system for its liquid oceans and seas. Where did all this water come from? There was water in the disc of dust and gas from which the solar system formed, but some scientists believe the inner region of this disc where the Earth formed was too hot for water.⁷ They contend that icy comets and asteroids delivered water from the further reaches of the solar system long after Earth's formation. This barrage goes on today; every few seconds a 'snowball' the size of a large truck melts into the outer atmosphere. But measurements of the isotopic composition of these snowballs suggest they only contributed a few per cent of our water.⁸ Meteorites were assumed to have delivered most of the rest, but recently a comet has been found with a very similar isotopic composition of water to Earth's oceans, so comets could have contributed a bigger share than once thought.⁹ Another view is that water molecules drifting in space stuck to particles of dust, and that rock and water came together at the same time. Our world actually has enough water for five to ten oceans, perhaps more; most remains trapped within the bedrock. By weight, about half a per cent of basalt rock is water, trapped within the mineral lattice.¹⁰ As the early world heated up and rocks melted, water boiled off into the atmosphere. For over a hundred million years, the oceans were in the sky as a dense shroud of vapour that churned above the glowing surface of our planet.

When the Earth cooled down a bit, a new rain began to fall, this time of scalding water. The downpour lasted for thousands of years and would be repeated several times over the next half billion years, as giant impacts from extraterrestrial debris boiled off the upper layers of the seas. For a half billion years more, the Earth continued to be struck by asteroids far bigger than the one that killed off the

dinosaurs 65 million years ago. Few traces of these impacts remain, for the Earth's crust is continuously reworked into the planet's interior, but we can read their fury from the moon whose cratered surface records the bombardment and which has remained immobile since it cooled.

To begin with, oceans covered most of the world. Their volume could have been twice that of the present seas.¹¹ Islands cropped up where blocks of the Earth's crust collided and volcanoes built ash and lava mountains, but there were no continents. Those came later and formed slowly. The world today is broken up into continents and sea because the crust is made up of two kinds of rock. Below the sea it is made of basalt and is slightly denser than the granites that make up the continents. Repeated re-melting in the furnace of our young world separated off the lighter granitic rocks that form today's continents from the basalt. Both kinds of rock float on a sea of hot, viscous magma in the Earth's mantle below, but the continents float higher. Like icebergs, how much you see above water depends on how much lies unseen. Continents have deep roots so they float higher in the mantle than the oceanic crust. This is why the average height of land is 840 metres above sea level, while the average depth of the oceans is 3,680 metres, a consequence of the different densities of their rocks.¹²

To us, the oceans are immense. They cover 360 million square kilometres and fill a volume of 1.33 billion cubic kilometres. It is hard to imagine a cubic kilometre. If you flooded all of New York's Central Park with water to the height of a thirty-storey building, that would be about half a cubic kilometre: it would take 2.66 billion Central Parks of water to fill the oceans, an almost unthinkable volume. Yet at the scale of the planet, the oceans form a layer only as thick as the skin of an apple.¹³

The sticky magma of the Earth's mantle keeps the world's surface in constant motion. Hot magma rising from deep down creates new crust in some places. Since the world is not getting bigger, that creative force is matched by destruction somewhere else as crust slides back into the mantle. The Earth's surface is thus divided into blocks, called plates, which move in a slow-motion geological dance through time. Here again, the density difference between oceanic and continental crusts comes into play. Because oceanic crust is thin and

dense (four to ten kilometres thick, compared to the thirty to forty kilometres of most continental granite), it is recycled quickly into the mantle, about ten times more quickly than the continents. (None of the oceanic crust is greater than 200 million years old, whereas about 7 per cent of land is older than 2.5 billion years.¹⁴) Think of the continents as the froth bobbing on a pool beneath a waterfall. The water pours on beneath, but the froth endures.

Continents began to form very early on. To begin with crust was recycled quickly on a hot Earth, but the rate slowed as the planet cooled and the intense meteorite bombardment came to an end four billion years ago. Continents grew over time and reached roughly their present landmass 2.5 billion years ago. From then on, they have been recycled at about the same rate as they are created. Today, the plates creep slowly; the Atlantic Ocean is opening at an inch a year, a little slower than fingernails grow.

Zircons aside, the oldest rock in the world is the 4-billion-year-old Acasta Gneiss outcrop in northern Canada. This formed deep underground so it tells us little about what was going on at the surface. The oldest surface rocks are the highly metamorphosed Isua sediments of southern Greenland, which formed underwater and give us the first direct evidence of oceans.¹⁵ Remarkably, these deposits suggest that life had already evolved by the time they were formed. There are no fossils in the Isua sediments, but the chemical composition of carbon buried in these rocks is characteristic of the presence of life.

The first life forms evolved in the early Archean Eon – the billion and a half year eon that followed the Hadean. It was a very different world from the one we live in today. There was almost no free oxygen for a start, and the sun burned a quarter less brightly.¹⁶ Sometime between 3.8 and 4.1 billion years ago, microbes evolved that produced methane, a greenhouse gas twenty-five times more powerful than carbon dioxide.¹⁷ Methane levels rose and the planet warmed.¹⁸ For over a billion years, until at least 2.5 billion years ago, the greenhouse shroud sustained the liquid seas as the sun's fire warmed the Earth. If it hadn't been for this dense blanket of gases in the atmosphere, the oceans would have frozen and life might never have kindled, or it could have started only to be snuffed out early on.

For hundreds of millions of years after the first spark of life, there

is not a trace or shadow of its form in the rocks beyond chemical alterations.¹⁹ But spectacular recent advances in genetics and computing enable us to grow the tree of life backwards, from its leaves to the tip of the root from which it sprang. Every living thing, from the humblest virus to the greatest of the whales, shares a common heritage that is written in their genes. That similarity tells us, just as Charles Darwin predicted, that everything living today is descended from life's primordial spark. The genes that code for different metabolic functions can be placed in position on the tree of life to show the sequence of their emergence, and something of their timing. They tell us when life passed critical evolutionary milestones and from them we can infer how the environment was changing. In some cases, early life forms had to respond to planetary upheavals, but often they were themselves responsible for changing the world around them.

In the deep sea one can find hot springs under intense pressure that spew forth water superheated to 300–400°C and so laden with minerals that their plumes are opaque black or white. They deposit metal-rich compounds nearby that might have catalysed important chemical reactions. Today these hot springs support rich communities based entirely on energy captured from chemical reactions undertaken by microbes. Here, then, is a vestige of how the earliest microbes might have made their living, perhaps even of the place where life itself was forged.

For more than 3 billion years, the planet was ruled by singleton cells and microbial slime. It is hard to grasp such a vast timescale. Think of it this way: if every one of those years lasted just a second, it would take ninety-five years for 3 billion to pass by. Microbes evolve fast because they have fleeting generations. Even taking into account the likelihood that Archean oceans were far less productive than our own, there was time for hundreds of billions of generations to come and go.²⁰ Every new generation offered the possibility of variations that were the raw material of evolutionary innovation. This was a time of extraordinary inventiveness, when the foundations were laid for almost everything that life does today.

Early on, microbes developed the ability to produce energy by converting hydrogen sulphide – the gas that gives rotten eggs their smell

and that pours forth from deep sea hot springs – into sulphates.²¹ This was an essential step. Some developed complex chemical machinery to draw energy from sunlight to accomplish this conversion in shallow waters, and photosynthesis was born. Microbes are not easily fossilized, but they do get petrified into flinty rocks called chert. The earliest fossils are microscopic microbe threads locked into 3.45-billion-year-old Australian cherts, although their interpretation is controversial.²² They look like cyanobacteria, a group still common today. These were the creatures that would later on develop photosynthesis, the method of generating energy from sunshine that dominates all primary production today. They used the sun's energy to create carbon compounds – food in other words – from carbon dioxide and water. Their waste product was oxygen.

The first chemical traces of oxygen-producing photosynthesis were found in 2.7-billion-year-old shales rich in organic matter.²³ We must thank this innovation for the way our world works because this kind of photosynthesis has produced essentially all of the free oxygen around us today. It took hundreds of millions of years to make enough oxygen for us to detect its traces. Dark shales from Mount McRae in Western Australia, laid down 2.5 billion years ago, give us the first whiff of oxygen.²⁴

Soon after (at least in geological terms, since it took another 50 million years), we begin to find evidence of oxygen in rocks all over the world. The next 150 million years is known to geologists as the 'Great Oxidation Event', because it heralds the first major step in the formation of the atmosphere we have today. Far from being a boon (that would come later), oxygen first plunged the Earth into a crisis. When oxygen and methane get together, the result is carbon dioxide and water. Carbon dioxide is twenty-five times less powerful a greenhouse gas than methane, so the Earth's comfort blanket thinned and the planet froze.

This ice age is thought by some scientists to have been so severe that the sea and continents iced over all the way to the tropics.²⁵ When ice forms at latitudes lower than about 30°, it reflects so much heat back into space that glaciation runs away with itself. Some simulations of such a world suggest that the oceans could freeze to a thousand metres deep. The ice would only have retreated after millions of years

of volcanic activity had added enough carbon dioxide to the atmosphere to warm Earth enough to melt it. It is hard to see how life could have survived a 'Snowball Earth', so one suggestion is that the tilt of the planet in relation to the sun must have been different at this time, so that the poles were warmer than the tropics and ice-free conditions persisted through the great freeze in some places.²⁶ Another possibility is that weather systems kept some areas of ocean ice free.

The oceans of the past were not places in which you would have wanted to swim. In Hadean and Archean times they are thought to have been rich in dissolved iron and anoxic, or oxygen-free. The iron came from deep-sea hot springs and weathered rock. In the absence of oxygen, iron dissolves and is easily washed to sea, whereas if oxygen is present iron oxides tend to stay put. Early microbes put this iron to work. They developed ways to use the power of sunshine to oxidize free iron and make food from carbon dioxide and water. Iron was precipitated at the bottom of these seas to form thick deposits known today as banded iron formations.²⁷

A slice of 2.5-billion-year-old seabed sits on my shelf at home. It is only a centimetre thick, but is surprisingly heavy. Wavy layers of rust brown, yellow and orange silica alternate through the slab with dark black and grey stripes of magnetite. Thicker layers of shimmering tiger eye fill gaps where the rock was later twisted and deformed under pressure. It is beautiful. I find it amazing to run my finger across this fragment of our primordial ocean. Most banded iron formations have long since been recycled back into the Earth's mantle, but bits of ancient seabed lie stranded in rock formations in Australia, Canada, Russia and elsewhere to form some of the richest sources of iron ore in the world. Banded iron formations are largely confined to rocks older than 2.4 billion years. They disappear from the record for the next 400 million years. For a long time it was thought that free oxygen produced by cyanobacteria had dissolved in the ocean and stripped it of iron, but another possibility now seems more likely, based on the chemistry of rock deposits. Donald Canfield, a polymath geobiologist based in Denmark, thinks that below a thin surface layer, the sea had no oxygen for hundreds of millions of years after oxygen first began to rise in the atmosphere. His idea is that oxygen

reacted with sulphides in terrestrial rocks and washed into the sea as sulphate. It was the sulphate that stripped the oceans of their iron, not the oxygen. The Great Oxidation Event would not penetrate to the deep sea until a billion years later.

Why did it take so long to ventilate the deep? Oxygen levels in the atmosphere were still very low, no more than about 1 per cent of today's level. We would have suffocated in no time. Oxygen is transported to the deep sea when surface waters plunge down, but it is used up breaking down organic matter – dead microbes in other words – that sinks from the surface. It would not take much sinking organic matter to strip oxygen from the deep faster than it could be replaced. Still, it is hard to explain how deep water could remain oxygen-free for such an immense stretch of time after the rise of oxygen-producing photosynthesis. Early oxygen-producers lived in shallow sunlit waters. Just like life today, they needed nutrients to fuel their growth as well as sunshine. Since most nutrients sink with the dead bodies of microbes, they have to be recycled by the upward mixing of deep water. An intriguing new idea is that anoxic waters, rich in hydrogen sulphide, reached up into the lower sunlit layer²⁸ where they encountered photosynthesizers that used up hydrogen sulphide but didn't make oxygen, and who intercepted most of the nutrients before they could reach the oxygen-producing cells closer to the surface.²⁹ There is another twist in the nutrient tale. Very early on, life incorporated the trace metals iron and molybdenum into enzymes that fix nitrogen, thus securing one of life's essential nutrients. Sulphidic seas would have little of either of these metals, because both would have reacted with hydrogen sulphide and been deposited at the seabed. So it was that quirks of oceanography and nutrient supply appear to have held back planetary oxygenation for what seems like an eternity.

There are still places today where sulphur-based photosynthesis continues. The Black Sea is an almost completely enclosed basin of water which is capped by a warm sunlit surface layer that is less dense than the cool water underneath. Little of the oxygen in this warm surface layer mixes downward, so, below about 150 metres, the Black Sea has not had any oxygen for thousands of years. If you were to somehow bring a sample to the surface, it would stink of rotten eggs, just as the sulphidic ancient oceans would have. As this anoxic water nears

the surface, green and purple sulphur bacteria use sunlight to produce food and energy, just as their predecessors did eons ago.

It is hard to know if all the world's oceans were once sulphidic like today's Black Sea. Most of the rocks that could tell us were long ago recycled back into the mantle, so there are few places to look for clues. What we do know is that 800–900 million years ago conditions began to change. What palaeontologists refer to as the 'boring billion years' ended. This period saw a shift in ocean chemistry towards the composition of modern oceans. A phase of intense mountain building around this time may have enhanced the delivery of trace nutrients to surface waters, enabling oxygen-producers to flourish. With rising oxygen in the atmosphere, the sea became ventilated beyond the lower limit of the sunlit layers, ending the hegemony of the sulphur bacteria and freeing more nutrients for oxygen-producers. This positive feedback loop led gradually to the irreversible oxygenation of our atmosphere. It set the scene for life's next great innovation: multicellularity.

When Charles Darwin wrote *On the Origin of Species*, the fossil record seemed to fizzle out at the onset of the great Cambrian explosion, when life forms with hard body parts which readily fossilized first came into being. Before that, nothing: the rocks appeared blank. It was as if some creator had conjured forth a menagerie of primitive life that would later diversify into all subsequent beings. It has taken 150 years of intensive searching to find the enigmatic shadows of earlier life, much of it microbial, but it is there. Darwin would have loved to know what we know today.

Oxygenation of the Earth's atmosphere was a key event in the history of life. A metabolism based on oxygen respiration produces sixteen times more energy than equivalent anoxic pathways. When free oxygen became available, it created tremendous opportunities that were soon realized. The first oxygen-using enzymes have been traced by following the evolution of proteins back in time using the latest genetic sequencing libraries and powerful computer techniques. Although there are precious few pre-Cambrian fossils, in a sense every one of us contains a fossil library of genes that goes all the way back to the Archean Eon, billions of years ago. The history of changing

protein shapes gives us a molecular clock from which we can read the time when new innovations first emerged. The first hesitant steps towards the use of free oxygen seem to have been taken 2.9 billion years ago, 400 million years before the first clear evidence of free oxygen appears in the rocks.³⁰ Proteins involved in oxygen metabolism multiply quickly through the Great Oxidation Event. Then there is a second wave of evolutionary innovation in oxygen use that begins about 1.2 billion years ago and continues all the way to the Cambrian explosion of life. By the onset of the Cambrian Period, 542 million years ago, atmospheric oxygen had increased to about 12 per cent of today's level.

Oxygen is produced by photosynthesis when organic matter is created, and consumed both by respiration and by the decay of that organic matter. If the two sides of the equation were exactly balanced, oxygen would not build up in the air. But some organic matter is buried at the bottom of the sea or in swamps and lake beds. During late pre-Cambrian times, when oxygen levels in the atmosphere rose, the rate of organic carbon burial must have increased. Free oxygen is also produced when sulphate combines with iron to produce iron sulphide (pyrite or fool's gold). So, increased rates of pyrite burial would also oxygenate the world. We don't know exactly what caused burial rates to increase, but the oxygenation of the oceans is believed to have played a key role.

Whatever the cause, there are many who think that rising oxygen levels paved the way for life's explosion. The two go hand in hand. Large-bodied aerobic animals need enough oxygen to ventilate their tissues. Their virtual absence in the previous 3 billion plus years of life might just be because their size was impossible until oxygen levels rose high enough to sustain such bulk.

The Cambrian Period was a time of amazing evolutionary creativity. Within 20 million years we can read in the rocks the appearance of virtually every major animal group alive today. If periods are characterized by their most successful creatures, this was the age of the arthropods, distinguished by their external skeletons and jointed legs. Insects, crabs, lobsters, millipedes, spiders and the like are all their living descendants. But the now extinct trilobites really define the Cambrian Period better than any other group. Cambrian seas were

full of a bewildering mix of these low-bodied, scuttling creatures that wore articulated armour of body plates and helmets that were sometimes flamboyantly ornamented, with spikes and spines and compound eyes with crystalline lenses. Trilobites had good reason to defend themselves for there were predators about. One explanation for the Cambrian explosion sees it as an arms race in which some animals scrambled to escape or repel predators, while others developed ever better ways to catch prey. Grazing and predation pre-date the Cambrian Period by hundreds of millions of years, but it was then that the ability to swallow large prey was firmly established. The foundations of modern food webs were laid in Cambrian seas, during a period that came to a close 488 million years ago.

As life diversified, a series of environmental crises lopped branches from the spreading crown of the tree of life. Just when the atmosphere had become more breathable, anoxia returned to the oceans and sulphidic seas reappeared.³¹ What seems to have happened is that waters devoid of oxygen welled up on to shallow continental shelves, perhaps following rising sea levels, and snuffed out many trilobites and other creatures. Paradoxically, these crises may have driven atmospheric oxygen levels up. Ocean anoxia is linked to higher surface productivity and greater organic carbon burial in Cambrian oceans. Sinking faeces and dead plants and animals would descend faster out of the sunlit surface layers than the microbes of more ancient seas so more carbon would be buried, especially in anoxic waters where breakdown is sluggish. Free oxygen would get a boost.

The next leap forward in the construction of modern ocean ecosystems has again been linked to rising oxygen. It may come as a surprise to know that we owe the existence of sharks to the evolution of vascular land plants.³² These plants were the first to develop differentiated organs like leaves, roots and stems, and a complex architecture of tubes to conduct water, nutrients and food throughout their systems. This group includes ferns, club mosses, conifers and flowering plants, although the latter would come much later. Vascular plants debuted about 420 million years ago, and within 30 million years they had sprouted roots to draw nutrients from the soil and stabilize bigger growth forms. By 370 million years ago, plants had clothed the continents in a lush tangle of green.

How does this relate to sharks, you might ask. Roots and other adaptations to extract nutrients speeded the rate at which phosphate, a key plant nutrient, weathered from the soil and washed into the sea; marine productivity boomed, enabling longer food chains and bigger predators. At the same time, land plants massively increased organic carbon burial in swamps and, through run-off, in marine sediments. This brought the amount of oxygen up to levels similar to the present (21 per cent of the air), where they have stayed, give or take 5 per cent, for most of the last 350 million years. Freed from the constraint of low oxygen, the stage was set for active predators with big oxygen demands.

Animals a metre long were already present in late pre-Cambrian seas 580 million years ago. They were probably sedentary grazers or detritus feeders. Eighty million years on, there was more diversity and hunters emerged that were the size of a small child. Fast forward another 100 million years and the seas had filled with primitive fish, including the heavily armoured placoderms. By 370 million years ago, some had become terrifying beasts, large as buses. The predatory megafauna had arrived. Over the next 120 million years they were joined by sharks and reptiles such as ichthyosaurs, plesiosaurs and turtles. The predatory expansion reached its zenith recently, almost yesterday in geological terms. During the Miocene Epoch, which spanned 23 to 5 million years ago, giant sharks the size of great whales patrolled the seas and whales ate whales. There were formidable sperm whales the same length as today's, but with teeth three times as big. They have been named *Livyatan melvillei* after Herman Melville's mythic white whale.³³

The presence of these huge predators suggests seas more productive than our own. Indeed, the oceans and their life have had many ups and downs over the last 500 million years. The variety of life has gradually increased, but not in a steady rise, and not by the simple addition of new species to the existing inventory. The vast majority of species that have ever lived on Earth have disappeared. Five mass extinctions followed several crises that wiped out most of the trilobites during the Cambrian Period, possibly caused by the re-emergence of anoxic oceans.³⁴ The mother of all extinctions came 251 million years ago, at the end of the Permian Period. At this point, the fossils

of more than 90 per cent of marine species and two-thirds of terrestrial species simply disappear from the rocks. Before the Permian extinction, seabed sediments were filled with lively burrowing animals that churned them over and over. Afterwards, the sediments were nearly stilled.

What caused this cataclysm remains a source of heated argument, but the most likely cause was a half-million-year episode of volcanism that discharged 2 million cubic kilometres of basalt across the surface of what today is Siberia.³⁵ The lava flooded an area of 1.6 million square kilometres to depths up to 3,000 metres. It passed through layers of carbonate rock and coal to release massive quantities of carbon dioxide into the air. Prior to this, carbon dioxide had declined more than ten-fold since the Cambrian Period, and the loss of this greenhouse gas had driven the world into a glaciation that had lasted over 60 million years.

Now it gets hot. As carbon dioxide levels climbed the world warmed, and as it warmed the poles melted. Global temperatures spiked 6°C higher than today's. The oceans rose and the Arctic reached a balmy 15–20°C.³⁶ For reasons I will return to, this temporarily slowed deep-ocean mixing and the stagnant water warmed all the way down to the deep seabed. The warm conditions melted huge polar and undersea deposits of methane to cause runaway global warming. Land plants withered and soils washed away. The stagnant sea became anoxic in all but surface waters. Meanwhile, dissolved carbon dioxide turned the oceans more acid, which, again for reasons I will come back to, was disastrous for chalky animals like corals, urchins, calcareous seaweeds and sponges.³⁷ The mass extinction at the close of the Permian Period almost wiped life's slate clean. But life rose again. Within 10 million years, the oceans had refilled with new species.

Sitting in my garden one day thinking about this book, my mind wandered back to the world's origin 4.5 billion years ago. It is hard to believe that this world is the same as our own – our planet, hurtling through the emptiness of space, so alien yet so familiar. I imagine hitting the fast-forward button to see continents ascend, meander, coalesce and crumble; oceans rise and fall; seas, deserts and ice caps

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come and go. Within the belly of these oceans creatures outlandish and familiar, bizarre and terrifying appear and disappear. Great reefs are built, destroyed and remade. Life flourishes, is choked off and resurrects itself again and again. And through the strangeness and inconstancy swim turtles and sharks, nautilus and jellyfish, scarcely altered, like a connecting thread that reaches back through time. A moment before the tape ends we appear. All of us carry this thread within ourselves. We are creatures of the sea with a lineage that stretches back to sponges and beyond, all the way through single-celled microbes to life's origin. The rest of this book tells the story of what happened to the oceans after we arrived.