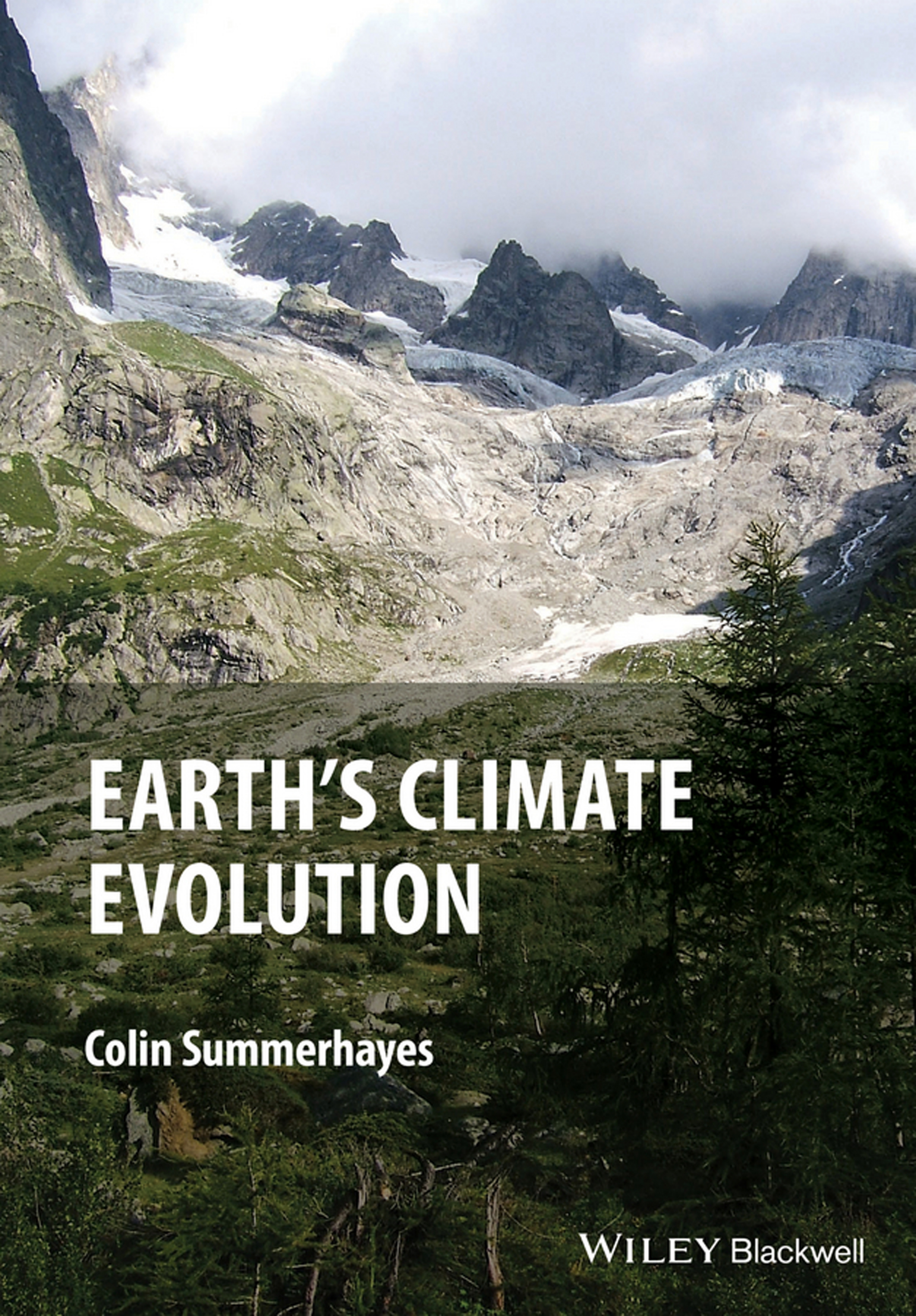

EARTH'S CLIMATE EVOLUTION

Colin Summerhayes

WILEY Blackwell

Earth's Climate Evolution

The Geological Time Scale for the Phanerozoic Aeon

Era	**Period**	**Epoch**	**Base Age (Ma)**
Cenozoic[a]	Quaternary	Holocene	0.0117
		Pleistocene	2.6
	Neogene	Pliocene	5.3
		Miocene	23
	Palaeogene	Oligocene	33.9
		Eocene	55.8
		Palaeocene	65.5
Mesozoic	Cretaceous	Upper	99.6
		Lower	145.5
	Jurassic	Upper	161.2
		Middle	175.6
		Lower	199.6
	Triassic	Upper	228.7
		Middle	245.9
		Lower	251
Palaeozoic	Permian	Upper	260.4
		Middle	270.6
		Lower	299
	Carboniferous	Upper	318.1
		Lower	359.2
	Devonian	Upper	385.3
		Middle	397.5
		Lower	416
	Silurian		443.7
	Ordovician		488.3
	Cambrian		542

[a]During the 19th century, geological time was divided into Primary, Secondary, Tertiary and Quaternary Eras. Mesozoic and Palaeozoic strata were regarded as belonging to the Secondary Era. The Tertiary was equivalent to the Cenozoic Era, but without the Quaternary. These older designations were done away with in the latter part of the 20th century, although 'Tertiary Era' is often misused for 'Cenozoic Era'. Of the older terms, 'Quaternary' has managed to hang on in the form of a geological period. From the International Stratigraphic Chart for 2010 (see http://www.stratigraphy.org/index.php/ics-chart-timescale, last accessed 29 January 2015).

Earth's Climate Evolution

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Cover image: The Glacier de Frébouze at the southern edge of the Mont Blanc Massif, taken from the south side of the Italian Val Ferret, near the Col de Ferret, looking north and showing bare rock exposed by glacial retreat, plus abundant scattered erratic blocks left by the shrinking glacier. © Colin Summerhayes, 2007

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To my grandchildren, Reid, Torrin and Jove Cockrell and Zoe and Phoebe Summerhayes,
in the hope that you can work towards freeing the future from the negative aspects
of anthropogenic climate change.

Contents

Author Biography

Colin P. Summerhayes is an emeritus associate of the Scott Polar Research Institute of Cambridge University. He has carried out research on past climate change in both academia and industry: at Imperial College London; the University of Cape Town; the Woods Hole Oceanographic Institution; the United Kingdom's Institute of Oceanographic Sciences Deacon Laboratory; the United Kingdom's Southampton (now National) Oceanography Centre; the Exxon Production Research Company; and the BP Research Company. He has managed research programmes on climate change for the United Kingdom's Natural Environment Research Council, the Intergovernmental Oceanographic Commission of UNESCO and the Scientific Committee on Antarctic Research of the International Council for Science. He has co-edited several books relating to aspects of past or modern climate, including *North Atlantic Palaeoceanography* (1986), *Upwelling Systems: Evolution Since the Early Miocene* (1992), *Upwelling in the Oceans* (1995), *Oceanography: An Illustrated Guide* (1996), *Understanding the Oceans* (2001), *Oceans 2020: Science, Trends and the Challenge of Sustainability* (2002), *Antarctic Climate Change and the Environment* (2009) and *Understanding Earth's Polar Challenges: International Polar Year 2007–2008* (2011). Photo courtesy of the author; taken amid the snows of the Lofoten Islands, Norway, April 2009.

Foreword

Climate change is becoming increasingly obvious, through melting glaciers, extreme weather events and rising insurance premiums. Research on the topic is reported and reviewed more thoroughly than any other aspect of the world we live in, and yet we allow the principal cause, greenhouse gas emissions, to continue to rise.

In the last few years, many eminent climate scientists have shifted their focus from seeking new knowledge to reviewing what we already know of our warming world and what our followers will have to cope with in the future. All conclude with a call for action. What makes this book different is its multi-million-year perspective, looking at the climate of the past. Surprisingly, it turns out not only to be relevant for appreciating what we will be facing in coming decades and centuries, but also to add to the urgency of the need for action.

Colin has had a remarkable career, beginning in the 1960s as a scientist in the early days of the plate tectonics revolution, making discoveries in ocean circulation in the 1970s, and then in the 1980s moving into petroleum exploration to reconstruct geography and environments in the distant past to help find more oil. Since then, he has worked with UNESCO's Intergovernmental Oceanographic Commission and the World Meteorological Organization on the contribution of the oceans to modern climate change, going on to the Scientific Committee on Antarctic Research to oversee the development of Antarctic multidisciplinary studies of climate change and its effects on all time scales from the distant past to the future. His stories remind us that scientists are also human.

The real stimulus for this book came recently, through his realisation that many colleagues were still climate change 'sceptics', actively persuading the public that changes in climate in recent decades were either not significant or not related to greenhouse gas emissions, or both. First, he led a group within the Geological Society of London to develop a position paper for the Society on the issue. This paved the way for taking the case to the public through this book.

The story is a fascinating one, for a number of reasons. It reveals how much of our current understanding of Earth's climate history and the role of atmospheric CO_2 has been known for well over a century. In the 1830s, Charles Lyell, Father of Geology, described the great cooling of the last 50 million years, leading to the Ice Age of the last 2 million years. By 1896, Svente Arrhenius, at the behest of a geological colleague, had estimated the climatic consequences of increasing CO_2 levels in the atmosphere. Since then, this basic understanding has been improved upon and verified in remarkable detail through advances in imaging strata beneath the Earth's surface, and in determining environmental conditions (including temperature and atmospheric CO_2 levels) at various times and places in the past from ice and sediment cores going back tens of millions of years.

Colin also includes in his story the most recent scientific tool of all, numerical simulation of Earth's climate through computer modelling of various interactions involving atmosphere, water on land and in the oceans, snow and ice and the living world. These models are of course the only means we have for making projections of future climate, providing a rational basis for assessing possible consequences for both the physical and biological worlds. After 40 years of development, and astonishing advances in computer power, we now find broad agreement between model estimates of past climate and geological knowledge of the same periods, but also some mismatches, as well as significant differences between results from different modelling groups. As you'll see from Colin's overview of the field, the crucial issues are now in finding ways of increasing the robustness of the models for projecting regional consequences of climate change. However, critical issues, such as how fast these changes will be, have yet to be resolved, with ice loss and sea level rise a key concern.

Three aspects of the book are especially significant. The first is the extensive knowledge of the details of Earth's climate and its interaction with the ocean. These are not only captured from observations over the last 150 years and modelling in the last 30, but now include similar studies covering the period since the Last Glacial Maximum 20 000 years ago, and into the stable warm climate of the last 10 000 years, which led to the development of agriculture and our present society. We also get confirmation of the temperature–CO_2 link from much warmer times millions of years ago, reflecting Earth's future climate, to which all species (not just us) will have to adapt by 2100 if present emission rates continue. While our understanding of the Earth system is not complete, it is nevertheless huge, and fully justifies our confidence in acting on this new knowledge. The second aspect is the abundant evidence that Earth is now warming beyond the 'natural envelope' of the Ice Age glacial–interglacial climate cycles of the last 2.6 million years, a development that is becoming increasing significant for all life on Earth. The third is our growing appreciation that there is a lag between increasing greenhouse gas levels in the atmosphere and the response of warming of the atmosphere (more or less instantaneous), of the oceans (in decades to centuries) and of the ice sheets (decades to millennia). On the bright side, this gives us some time to act, but our geological knowledge shows us the ultimate consequences of not changing our present course. We might be able to cope with warmer temperatures in most places, but sea level rise of 10–20 metres in several hundred years will be more difficult. That prospect now seems inevitable, though we can still delay the worst if we reduce our emissions in coming decades. Earth has been there before, but change came slowly. Do we want to get there in a geological instant?

Beyond the message from climate science itself, Colin also provides intriguing glimpses of how scientists in the past were regarded by their contemporaries, and the context in which they worked. Some were very effective networkers long before the Internet age! I hope readers will also enjoy discovering from these pages how science makes progress, despite the human limitations to which we are all subject – occasionally pausing, but in the end always self-correcting.

P.J. Barrett
Fellow of the Royal Society of New Zealand
Holder of the NZ Antarctic Medal
Honorary Fellow, Geological Society of London
Emeritus Professor of Geology, Victoria University of Wellington
Wellington, New Zealand

Acknowledgements

Research for an all-embracing book like this is impossible without the help of many people. I thank Julian Dowdeswell for facilitating my research by making me an emeritus associate of the Scott Polar Research Institute.

The concept for the book emerged from the workings of the drafting group that produced the policy statement on climate change for the Geological Society of London (GSL) (www.geolsoc.org.uk/climaterecord). I am grateful to a former president of the GSL, Lynne Frostick, for appointing me in January 2010 to chair that group. My understanding of Earth's climate evolution was broadened through stimulating discussions with the members of the drafting group that produced that statement in November 2010 and its addendum in 2013, including Jane Francis, Alan Haywood, Joe Cann, Anthony Cohen, Rob Larter, Eric Wolff, John Lowe, Nick McCave, Paul Pearson and Paul Valdes, aided by Edmund Nickless, Nic Bilham and Sarah Day. The GSL's librarians, Michael McKimm, Wendy Cawthorne and Paul Johnson, helped me find a number of obscure publications.

Many individuals donated time and effort to helping me with advice or materials or discussions along the way. They included Ian Jamieson (Guildford), Vicki Hammond (Edinburgh), Peter Barrett (Wellington), Mike Sparrow, Eric Wolff, Marie Edmonds, Bryan Lovell, John Turner and Tom Bracegirdle (Cambridge), Peter Liss and Andy Watson (Norwich), Jane Francis (Leeds), Paul Mayewski (Maine), Martin Siegert and Cherry Lewis (Bristol), Valérie Masson-Delmotte (Gif-sur-Yvette), Phil Woodworth (Liverpool), Bob Berner (Yale), Terrence Gerlach (US Geological Survey), Peter Dexter (Melbourne), Chris Scotese (Arlington, Texas), Judy Parrish (Idaho), Cornelia Lüdecke (Munich), Jörn Thiede (Kiel), Heinz Wanner (Bern), David Bottjer (Los Angeles), Jim Kennett (Santa Barbara), Alan Lord (London), Iain Stewart (Plymouth), Mike Arthur (Penn State), Chris Rapley (UCL), Pieter Tans (NOAA), Malcolm Newell and Ralph Rayner (IMarEST, London), Keith Alverson (UNESCO, Paris), Ed Sarukhanian (WMO, Geneva), John Gould (Southampton), Eric Steig (Washington State), Bob Binschadler (NASA), Emily Shuckburgh (Oxford), Bryan Storey (Christchurch), John Lewis (NOAA), André Berger (Louvain) and David Archer (Chicago). I apologise if I have inadvertently left anyone out. Any errors in the text are my own. I have drawn extensively on findings published in the scientific literature, which is a vast storehouse of accumulated learning about all aspects of our climate history. Those writings, integrated together, tell a compelling story that I have tried to put into a form that anyone with a basic scientific education can understand. My gratitude goes to the thousands of scientists who have dedicated themselves to making the individual bricks in this impressive wall. I would also like to thank the many audiences in schools, universities, womens' groups, and mens' business groups, on whom I have tried out my ideas, and who have stimulated me with their probing questions. That list includes the many participants of Antarctic cruises on 'Le Boreal'.

Last but not least, I would like to thank my grandson, Reid Cockrell, for culling articles on global warming from my back issues of *Nature* and *New Scientist* and for indexing the book, and my long-suffering wife, Diana, for putting up with my mental absences on Planet Climate. Yes, that's where I was in those moments when my eyes were glazed and I didn't hear the question.

1

Introduction

In almost every churchyard, you'll find gravestones so old that their inscriptions have disappeared. Over the years, drop after drop of a mild acid has eaten away the stone from which many old gravestones were carved, obliterating the names of those long gone. We know this mild acid as rainwater, formed by the condensation of water vapour containing traces of atmospheric gases like carbon dioxide (CO_2) and sulphur dioxide (SO_2). It's the gases that make it acid. Rain eats rock by weathering.

Weathering is fundamental to climate change. Over time, it moves mountains. Freezing and thawing cracks new mountain rocks apart. Roots penetrate cracks as plants grow. Rainwater penetrates surfaces, dissolving as it goes. The CO_2 in the dissolved products of weathering eventually reaches the sea, where it forms food for plankton, and the seabed, in the remains of dead organisms. Once there, it goes on to form the limestones and hydrocarbons of the future; one day, volcanoes will spew that CO_2 back into the atmosphere and the cycle will begin all over again.

The carbon cycle includes the actions of land plants, which extract CO_2 from the air by photosynthesis. When plants die, they rot, returning their CO_2 to the air. Some are buried, preserving their carbon from that same fate, until heat from the Earth's interior turns them back into CO_2, which returns to the air. This natural cycle has been in balance for millions of years. We have disturbed it by burning fossil carbon in the form of coal, oil or gas.

This book is the story of climate change as revealed by the geological record of the past 450 million years (450 Ma). It is a story of curiosity about how the world works and of ingenuity in tackling the almost unimaginably large challenge of understanding climate change. The task is complicated by the erratic nature of the geological record. Geology is like a book whose pages recount tales of the Earth's history. Each copy of this book has some pages missing. Fortunately, the American, African, Asian, Australasian and European editions all miss different pages. Combining them lets us assemble a good picture of how Earth's climate has changed through time. Year by year, the picture becomes clearer, as researchers develop new methods to probe its secrets.

As we explore the evolution of Earth's climate, we will follow the guidance of one of the giants of 18th-century science, Alexander von Humboldt, who wrote in 1788, '*The most important result of research is to recognize oneness in multiplicity, to grasp comprehensively all individual constituents, and to analyze critically the details without being overwhelmed by their massiveness*'[1]. All too often, those who seek to deny the reality of modern climate change ignore his integrative approach to understanding nature by focusing on just one or two aspects where the evidence seems, at the moment, to be less than compelling.

Can the history of Earth's climate tell us anything about how it might evolve if we go on emitting gigatonnes (Gt) of CO_2 and other greenhouse gases into the atmosphere? That is the key question behind the title to this book. I wrote it because I have spent most of my career working on past climate change, and it worries me that few of the results of the growing body of research on that topic reach the general public. Even many professional Earth scientists I meet, from both academia and industry, know little of what the most up-to-date Earth science studies tell us about climate change and global warming. For the most

Earth's Climate Evolution, First Edition. Colin P. Summerhayes.

part, they have specialised in those aspects of the Earth sciences that were relevant to their careers. Unfortunately, their undoubted expertise in these topics does not prevent some of them from displaying their ignorance of developments in the study of past climate change by trotting out the brainless mantra, 'the climate is always changing'. Well, of course it is, but that ignores the all-important question: Why?

What we really need to know is in what ways the climate has been changing, at what rates, with what regional variability, and in response to what driving forces. With these facts, we can establish with reasonable certainty the natural variability of Earth's climate, and determine how it is most likely to evolve as we pump greenhouse gases into the atmosphere. This book attempts to address these issues in a way that should be readily understandable to anyone with a basic scientific education. It describes a voyage of discovery by scientists obsessed with exposing the deepest secrets of our changing climate through time. I hope that readers will find the tale as fascinating as I found the research that went into it.

The drive to understand climate change is an integral part of the basic human urge to understand our surroundings. As in all fields of science, the knowledge necessary to underpin that understanding accumulates gradually. At first we see dimly, but eventually the subject matter becomes clear. The process is a journey through time, in which each generation makes a contribution. Imagination and creativity play their parts. The road is punctuated by intellectual leaps. Exciting discoveries change its course from time to time. No one person could have discovered in his or her lifetime what we now know about the workings of the climate system. Thousands of scientists have added their pieces to the puzzle. Developing our present picture of how the climate system works has required contributions from an extraordinary range of different scientific disciplines, from astronomy to zoology. The breadth of topics that must be understood in order for us to have a complete picture has made the journey slow, and still makes full understanding of climate change and global warming difficult to grasp for those not committed to serious investigation of a very wide-ranging literature. The pace of advance is relentless, and for many it is difficult to keep up. And yet, as with most fields of scientific enquiry, there is still much to learn – mostly, these days, about progressively finer levels of detail. Uncertainties remain. We will never know everything. But we do know enough to make reasonably confident statements about what is happening now and what is likely to happen next. Looking back at the progress that has been made is like watching a timelapse film of the opening of a flower. Knowledge of the climate system unfolds through time, until we find ourselves at the doorstep of the present day and looking at the future.

While the story of Earth's climate evolution has a great deal to teach us, it is largely ignored in the ongoing debate on global warming. The idea of examining the past in order to discover what the future may hold is not a new one. It was first articulated in 1795 by one of the 'fathers of geology', James Hutton. But it is not something the general public hears much about when it comes to understanding global warming. This book is a wake-up call, introducing the reader to what the geological record tells us.

Information about the climate of the past is referred to as 'palaeoclimate data' (American spelling drops the second 'a'). As it has mushroomed in recent years, it has come to claim more attention from Working Group I of the Intergovernmental Panel on Climate Change (IPCC). The Working Group comprises an international group of scientists, which surveys the published literature every 5 years or so to come up with a view on the current state of climate science. It has been reporting roughly every 5 years since its first report in 1990. Each of its past two reports, in 2007[2] and 2013[3], incorporated a chapter on palaeoclimate data. The Working Group's report is referred to as a 'consensus', meaning the broad agreement of the group of scientists who worked on it. Just one chapter in a 1000-page report does not constitute a major review of Earth's climate evolution: the subject deserves a book of its own, and there are several, as you will see from the Appendix to the present book.

The study of past climates used to be the exclusive province of geologists. They would interpret past climate from the character of rocks: coals represented humid climates; polished three-sided pebbles and cross-bedded red-stained sands represented deserts; grooved rocks indicated the passage of glaciers; corals indicated tropical conditions; and so on. Since the 1950s, we have come to rely as well on geochemists using oxygen isotopes and the ratios of elements such as magnesium to calcium (Mg/Ca) to tell us about past ocean temperatures. And in recent years we have come to realise that cores of ice contain detailed records of past climate change, as well as bubbles of fossil air; glaciologists have joined the ranks.

Climate modellers have also contributed. Since the 1950s, our ability to use computers has advanced apace. We now use them not only to process palaeoclimate data and find correlations, but also to run numerical models of past climate systems, testing the results against data from the rock record. Applying numerical models to past climates that were much colder or much warmer than today's has an additional benefit: it helps climate modellers to test the robustness of the models they use to analyse today's climate and to project change into the future. One of my reasons for writing this book is to underscore how research into past climates by both of these research streams, the practical and the theoretical, adds to our confidence in understanding the workings of Earth's climate system and in predicting its likely future.

My take on the evolution of Earth's climate is coloured by my experience. Early in my geological career, I applied knowledge of how oceans and atmospheres work to interpret the role of past climates in governing the distribution of the phosphatic sediments that form the basis for much of the fertiliser industry. That work broadened into a study of how climate affects runoff from large rivers like the Nile and the Amazon, as well as the accumulation of sediments on the world's continental shelves. Working for Exxon Production Research Company (EPRCo) in Houston, Texas, in the mid-1970s, I developed a model for how climate controlled the distribution of petroleum source beds: rocks rich in organic remains that, when cooked deep in the subsurface, yield oil or gas. Explorers tested my model's predictions by drilling. Later, with the BP Research Company (BPRCo), I studied how the changing positions of past continents, along with changing sea levels and climates, affected the distribution and character of sources and reservoirs of oil and gas, as the basis for developing predictions for explorers to test by drilling.

In the late 1980s to mid-1990s, as director of the UK's main deep-sea research centre, the Institute of Oceanographic Sciences Deacon Laboratory, I learned a great deal more from my physical, biological and chemical oceanographer colleagues about the ocean's role in climate change. I applied that knowledge to analysing the response of the upwelling currents off Namibia and Portugal to the glacial-to-interglacial climate changes of the last Ice Age.

In order to develop accurate forecasts of climate change, one has to have an observing system, much like that used for weather forecasting. In 1997, I joined UNESCO's Intergovernmental Oceanographic Commission (IOC) to direct a programme aimed at developing a Global Ocean Observing System (GOOS), which would provide the ocean component of a Global Climate Observing System (GCOS). The task further broadened my understanding of climate science. Then, from 2004 to 2010, I directed the Antarctic research activities of the International Council for Science (ICSU), while based at the Scott Polar Research Institute of the University of Cambridge. There I was awarded emeritus status, starting in 2010. These recent appointments exposed me to the thinking of the polar science community about the role of ice in the climate system. Few people can have been as fortunate as I in being exposed to the current state of knowledge about the operations of the climate system from the perspectives of the ocean, the atmosphere, the ice and the geological record.

Because of that diverse background, I was asked to advise the Geological Society of London on climate change. Many of the world's major scientific bodies, including the US National Academy of Sciences and the UK's Royal Society, have felt moved in recent years to publish statements on the science of global warming as part of their remit to inform the public and policy makers about advances in science. The Geological Society of London became interested in 2009 in developing such a statement, and its then president, Professor Lynne Frostick, invited me to chair the group that would draft it. Entitled 'Climate Change: Evidence from the Geological Record', the statement was published on the Society's Web page[4] and in its magazine, *Geoscientist*, towards the end of 2010[5]. I led basically the same team in writing an addendum to the statement in 2013, to show what advances had been made in the intervening 3 years and to provide a palaeoclimate-based statement that could be evaluated alongside the 5th Assessment Report of the IPCC's Working Group I, published in September 2013. We operated independently of the IPCC, and drew our own conclusions. The Society published the addendum in December 2013[4].

As the Society's statement was being developed, I realised that it did not allow the space to reveal either the human stories behind the long development of modern climate science or the full extent of advances emerging through palaeoclimatic research. So I resolved to write a book about climate change from the palaeoclimate perspective – the 'long' view – drawing on the Society's statement and summarising the history and knowledge of climate processes that took place over millions of years under conditions very different from today's. This book is the result. It shows how the climate record of past times is the key to understanding the natural variability of our climate, and explains why that knowledge is a necessary complement to what we learn from meteorologists and modern climatologists focusing on the instrumental records of the past 150 years.

The book focuses on the past 450 Ma or so of Earth's climate, starting with the period when land plants first emerged, because plants play an important role in tying up carbon on land. For most of the past 450 Ma, our planet has been a lot warmer than it is now. Our climate is usually of the greenhouse variety, with abundant CO_2 warming the part of the atmosphere in which we live: the troposphere. This long history of warmth is not widely recognised, because in the past 50 Ma Earth's atmosphere has lost much of its CO_2 and moved into an icehouse climate, characterised by cool conditions and polar ice. That cooling has intensified to the point where, over the past 2.6 Ma, Earth has developed large ice sheets in both polar regions. This period has earned a popular title: the Ice Age. We are living in a geologically brief warm interlude within that Ice Age. Before an ice sheet formed on Antarctica, 40–50 Ma ago, global temperatures were warmer by 4–6 °C than they are today. Where will our climate go next? Will we stay in the icehouse or move back into the greenhouse? The latest news from NASA's Jet Propulsion Laboratory, dated 12 May 2014, is that the West Antarctic Ice Sheet has begun an irreversible decline, making it likely that we are now moving away from the icehouse and towards the greenhouse[6].

Increasing scrutiny of the palaeoclimate record over the past few decades has helped us to explain why our present climate is the way it is. Most of the fluctuation from warm to cold climates through time takes place because of changes in the balance of Earth's interior processes. Changes over millions of years involve periods of excessive volcanic activity, associated with the break up and drift of continents, which fills the air with CO_2 and keeps the climate warm, and periods of continental collision, which build mountains and encourage the chemical weathering of exposed terrain, sucking CO_2 out of the atmosphere and keeping the climate cool. Continental drift moves continents through climatic zones, sometimes leaving them in the tropics, sometimes at the poles. It also changes the locations of the ocean currents that transport heat and salt around the globe. Individual volcanic eruptions large enough to eject dust into the stratosphere provide short-term change from time to time, while the equally erratic but more persistent volcanic activity of large igneous provinces, involving the eruption of millions of cubic metres of lava over a period of a million years or so, can change the climate for longer periods; at times, they may have done so enough to cause substantial biological extinctions.

External changes are important, too. The Sun is the climate's main source of energy. Orbital variations in the Earth's path around the Sun, combined with regular changes in the tilt of the Earth's axis, superimpose additional change on these millions-of-years-long changes, through cycles lasting 20 000 to 400 000 years (20–400 Ka). Variations in the Sun's output superimpose yet another series of changes, with variability at millennial, centennial and decadal scales. Examples include the 11-year sunspot cycle and its occasional failure. The best-known such failure is the Maunder Minimum between 1645 and 1715 AD, at the heart of the Little Ice Age. Large but rare meteorite impacts have had similar, albeit temporary, effects.

Internal oscillations within the ocean–atmosphere system, like El Niño events and the North Atlantic Oscillation, cause further changes at high frequencies but low amplitudes, and are usually regional in scope. Whatever the climate at any one time, it is modified by internal processes like those oscillations, and by the behaviour of the atmosphere in redistributing heat and moisture rapidly, by the ocean in redistributing heat and salt slowly and by the biota. An example of the latter is the 'biological pump', in which plankton take CO_2 out of surface water and transfer it to deep water and, eventually, to sediments, when they die. These processes can make attribution of climate change difficult, as can the smearing of the annual record in deep-water sediments by burrowing organisms.

In spite of the potential for considerable variation in our climate, close inspection shows that at any one time the climate is constrained within a well-defined natural envelope of variability. Excursions beyond that natural envelope demand specific explanation. As we shall see, one such excursion is the warming of our climate since late in the last century.

This book looks at these various processes and puts them into perspective in their proper historical context. Chapter 2 follows the evolution of thinking about climate change by natural scientists, philosophers and early geologists from the late 1700s on. It touches on the debates of the early 1800s on the virtues of gradual versus sudden change and highlights the growing realisation that the world cooled towards an Ice Age in geologically recent times. Chapter 3 takes us into the minds of 19th-century students of the Ice Age and examines the astonishing discovery that its climate cycles were probably controlled by metronomic variations in the behaviour of the Earth's orbit as it responded to the gravitational influences of the great gas planets, Venus and Jupiter.

The arrival of new technologies on the scene, often from different disciplines, changes the way in which science works; think of the effect of the telescope on Galileo's perception of astronomy. Geology is no exception. In Chapter 4, we explore the extraordinary mid-19th-century discovery of the absorptive properties of what we now know as the greenhouse gases, such as water vapour, carbon dioxide and methane, which changed the way we view past climates. At the end of that century, a Swedish chemist, Svante Arrhenius, made the first calculations of what emissions of CO_2 would do to the climate. Few people realise that he did so at the urging of a geological colleague, to try to see if variations in atmospheric CO_2 might explain the fluctuations in temperature of the Ice Age. An American geologist, Thomas Chamberlin, used Arrhenius's findings to construct an elegant hypothesis as to how CO_2 controlled climate, but it was soon forgotten for lack of data. Much of what he had to say on the subject has since been proved correct.

In Chapter 5, we examine the evolution of ideas in the early part of the 20th century about the way in which the continents move relative to one another through continental drift, which geophysicists discovered in the 1960s was driven by the process of plate tectonics. Once again, new technologies played a key role: in this case, the echo-sounder and the magnetometer. Knowing the past positions of the continents provides us with the maps of past geography – the palaeogeographic base maps – needed to determine the past locations of sedimentary deposits that are sensitive to climate, like coal swamps and salt pans. Along the way, we see how studies of past climates benefited from access to the accurate dating of rocks, minerals and fossils at the smallest possible intervals of time. Once again, a new technology was key: radiometric dating by the use of natural radioactivity.

Chapter 6 describes how the new science of palaeoclimatology developed, with Earth scientists plotting their indicators of past climates on maps, using yet another new technology – oxygen isotopes – to determine the temperature of past seawater. Geologists investigated the origins of sedimentary cycles, coming up with hypotheses explaining the evolution of climate from the Carboniferous glaciation roughly 300 Ma ago to the end of the Cretaceous at 65 Ma ago. Yet another new technology changed the picture again, this time in the shape of numerical models of the climate system, which capitalised on the rapid development of the computer. We see early attempts to use numerical models to find out why the Cretaceous Period was so warm, and note that until the mid-1980s, the analysis of palaeoclimates virtually ignored CO_2.

Chapter 7 takes us into the Cenozoic Era, which includes what used to be known as the Tertiary, between 65 and 2.6 Ma ago, and the Quaternary, lasting from 2.6 Ma ago to the present. Here we follow the cooling of our climate from the warmth of the Cretaceous seas that flooded western Europe and central North America 60–100 Ma ago to the current Ice Age, which characterises the Pleistocene Period (2.6 Ma to 11.7 Ka ago) and the present Holocene Period (starting 11.7 Ka ago). We look at how climate changed, and at how our knowledge of climate change was dramatically expanded by drilling into the largely undisturbed sediments of the deep ocean floor. As we saw in Chapter 6, many of the theories explaining the changes in climate of the Cenozoic Era prior to the 1980s developed in the absence of substantial knowledge about the past composition of the air.

A clear understanding of the roles of greenhouse gases in the climate system demands an ability to measure those gases and examine their properties: capabilities that were limited until the mid 1950s, and which then took another 30 years to penetrate the world of geological thought. Chapter 8 explores the massive strides made over the past 50 years in enhancing that knowledge base and in formulating theories to explain how greenhouse gases behave within the air and ocean. Along with that understanding came the realisation that, in order to understand the climate problem, we must see our planet holistically – as a whole – and not in a reductionist way. Humboldt was right: everything is connected. One key consequence was the development of a new field of scientific endeavour, biogeochemistry, which has proved especially important for understanding how the carbon cycle works. Answering questions about the evolution of the climate system also came to involve a more international approach, in which national scientists increasingly worked with each other across borders on major scientific issues such as climate change that were not susceptible to resolution by individual investigators or even individual nations.

Chapter 9 reminds us of the amazing discovery that ice cores contain bubbles of fossil air holding pristine samples of CO_2 and other greenhouse gases. We also see how palaeoclimatologists eventually learned how to measure the amount of CO_2 in the atmosphere in the ages before the oldest ice cores (which span the past 800 Ka) using fossil leaves, tree rings, planktonic remains, soils, corals and cave deposits. These data are being used to check numerical models of past climates and to test the theory that the warm periods of the past occurred when CO_2 was most abundant.

Our planet's climate has experienced large cycles through time. Chapter 10 explores how these cycles relate to changes in plate tectonic processes, sea level, emissions of CO_2 and the weathering of emerging mountain chains as continents collided. It investigates the evidence for changes to our climate, and the creation of major biological extinctions, caused by occasional meteorite impacts and/or massive eruptions of plateau basalts.

In Chapter 11, we examine the evidence for how CO_2 and climate changed together through the Mesozoic and Cenozoic Eras, and explore two case histories. The first is from the Palaeocene–Eocene boundary 55 Ma ago, when a massive injection of carbon into the air caused dramatic warming, which at the same time made the seas more acid. It took the Earth 100 Ka to recover – now, there's a lesson from the past! The second is from the mid-Pliocene, about 3 Ma ago, when CO_2 levels rose to levels much like today's, but when temperatures were warmer and the sea level was higher: another lesson from the past. These periods are not precise analogues for today, because the world was configured slightly differently then. But they can teach us something about what is happening now and what might happen in the future.

Chapter 12 begins our exploration of the Ice Age of the past 2.6 Ma, noting how much of what we know comes from cores of sediment extracted with great difficulty from the ocean bed. It was a big surprise in 1976 when it emerged that marine sediment cores display signs of change in the Earth's orbit and the tilt of the Earth's axis through time. These cores also display unexpected millennial signals.

Our exploration of Ice Age climate continues in Chapter 13, where we examine the contribution made by ice cores collected in recent decades. We see what the records tell us from Greenland and from Antarctica, and explore the linkages between the poles. The latest research shows that during the warming from the Last Glacial Maximum, CO_2 in the Antarctic region rose synchronously with temperature, not after it, as had been thought. The chapter ends with a survey of plausible explanations for the fluctuations of the Ice Age, concluding that CO_2 played a crucial role in the changes from glacial to interglacial and back over the past 800 Ka.

In Chapter 14, we focus on the changes that took place over the past 11.7 Ka, forming the latest interglacial: the Holocene. Insolation – the amount of heat received due to the motions of the Earth's orbit and the tilt of the Earth's axis – was greatest in the Northern Hemisphere at the beginning of the Holocene, but the great North American and Scandinavian ice sheets kept the Northern Hemisphere cool until they had completely melted by the middle Holocene. All that while, Northern Hemisphere insolation was in decline, moving Earth's climate towards a Neoglacial Period, the peak of which we reached in the Little Ice Age of the past few hundred years. CO_2 played no active part in this cooling.

Chapter 15 focuses on the end of the Holocene – the past 2000 years, up to the present – reviewing cyclical changes in solar output. It explores the development and extent of the Medieval Warm Period centred on 1100 AD and the subsequent Little Ice Age, and includes a review of the 'Hockey Stick' controversy. Multiple sources of palaeoclimatic data now make it abundantly clear that the years since 1970 were the warmest of the past 2000. Yet astronomical calculations show that despite variations in the sun's output, our climate should still be like that of the Little Ice Age. Only by adding our emissions of greenhouse gases like CO_2 to palaeoclimate models can we recreate the climate that we see today.

The concluding chapter, Chapter 16, provides an overview of Earth's climate evolution, concluding that, from the evidence of previous chapters, we should expect to see sea level rises of 6–9 m as temperatures rise 2–3 °C above the 'preindustrial' levels typical of the years before the Industrial Revolution. Those conditions were typical of recent interglacials, which were warmer than our own. We will not see such rises in sea level this century, because it takes a long time for the Earth system to arrive at an equilibrium, in which the ocean is heated as fully as it can be for a given level of atmospheric CO_2 and no more ice will melt.

As in any other field of science, the 200-year history of past climate studies has been punctuated with arguments and disagreements, but the influence of CO_2 on climate eventually emerged as highly significant. The exciting developments documented in this book revolutionised the way Earth science is done as much as did the discovery of plate tectonics. The demands of climate science now require sedimentologists and palaeontologists to become familiar with the host of related disciplines that deal with processes taking place on and above the Earth, and to take a holistic approach to interpreting their data. Due to the rapid evolution of these topics and techniques, including the use of computers to model palaeoclimate behaviour, much of what we now know is quite recent, and little publicised except in scientific journals.

In brief, the geological evidence now suggests that emitting further large amounts of CO_2 into the atmosphere over time will almost certainly push our climate from icehouse to greenhouse, something not experienced since the late Eocene about 40 Ma ago. We now have a strong enough base of geological evidence to agree that '*In the light of the evidence presented here it is reasonable to conclude that emitting further large amounts of CO_2 into the atmosphere over time is likely to be unwise, uncomfortable though that fact may be*'[4]. The evidence emerging from the past gives much the same answers about the nature of our future climate as those emerging from a different scientific community, the IPCC's Working Group I.

Hasn't all this been said before, in classical texts on palaeoclimatology? No, in the sense that my approach combines a depiction of the science with a study of its evolution and of the role of individuals and their imagination in reaching our current understanding of Earth's climate system. But there is growing appreciation that '*evidence from the Quaternary stratigraphic record provides key baseline data for predictions of future climate change*'[7].

Agreeing with Nate Silver[8], I argue that the way to test research findings like those laid out here is to see whether or not they make accurate predictions in the real world. Our ability to predict well is a measure of our scientific progress. If you start with an absolute belief that humans do not cause global warming then, following Bayes's Theorem, no amount of evidence will persuade you otherwise. But you have to recognise that what you hold is a belief, not scientific understanding.

One thing you will need to consider carefully is context. In this book you will see evidence that CO_2 does correlate with temperature. Correlation is not causation, but that is a trite observation that ignores context. When you know that CO_2 is a greenhouse gas that both absorbs and re-emits radiation, you should expect a correlation with temperature from that context. That's the prediction and it's easy to test. What then becomes interesting are the instances when the two do *not* correlate, for which we have to find alternative hypotheses. We have to think! Thus far, nobody has managed to explain what, if not our emissions of greenhouse gases and related feedbacks, has caused the global warming since 1970.

I will leave this introduction with two key questions for you to consider as you read on: **Can what we see of climate in the geological record tell us anything about what might happen if we go on emitting more and more carbon dioxide and other greenhouse gases into the atmosphere?** and **What are the chances that our increasing use of fossil fuels will drive Earth's climate out of the icehouse, where it has been stuck for several million years, and back into the greenhouse – the dominant climate mode for much of the past 450 million years?** We will revisit these questions at the end of the book.

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2

The Great Cooling

2.1 The Founding Fathers

Geologists have known for over 200 years that climate is one of the main controls on the accumulations of minerals and organic remains that end up as sedimentary rocks and fossils. As early as 1686, Robert Hooke, a fellow of London's Royal Society living in Freshwater on the Isle of Wight, deduced from fossils discovered at Portland that the climate there had once been tropical[1]. His perceptive observation remained unremarked upon until the keeper of France's Royal Botanical Gardens – the *Jardin des Plantes* – in Paris realised that differences in climate might explain the differences between living and fossil organisms found at the same place. This was the naturalist Georges-Louis Leclerc, the Comte de Buffon (1707–1788)[2], friend to Voltaire, and a member of both the French Academy of Sciences and the literary Académie Française.

Buffon planned to take his place in history with a vast 50-volume encyclopaedia: the *Histoire Naturelle, Générale et Particuliére*. The 36 volumes that he actually produced were among the most widely read publications of the time. His reconstruction of geological history appeared in 1788 in *Époques de la Nature*, the supplement to Volume 5. Buffon realised that each geographical region had its own distinctive plants, animals and climate – a basic principle of what we now call biogeography. Finding in Siberia and Europe the fossil remains of animals that now inhabit the tropics, he deduced that the climate there must have been warmer in the past.

Buffon thought that the temperature of the air reflected the temperature of the Earth, rather than the heat from the Sun, and interpreted animal remains to show that the Earth was cooling from its original molten state[2]. Sir Humphry Davy, FRS, discoverer of sodium and potassium and inventor of the coal miners' safety lamp, was another who shared this popular notion, penning it in 1829 in his *Consolations in Travel, or the Last Days of a Philosopher*, shortly before he died. Measurements of the temperature of the Earth and its atmosphere by the French scientist Joseph Fourier had knocked this idea on its head in 1824, however – an advance that Davy overlooked.

Buffon and other savants of the late 18th century considered that Earth's past history must be explained with reference to what is happening now[3]. Among them was James Hutton (1726–1797) (Figure 2.1), a Scot who profoundly influenced geological thought[4,5]. Born in Edinburgh, Hutton studied medicine and chemistry there and in Paris and Leyden. Taking up farming, first in Norfolk, then on his paternal acres in Berwickshire, he developed an interest in geology, and exploited his chemical knowledge to become partner in a profitable sal ammoniac business. By 1768, he was established in Edinburgh, pursuing his geological interests. In 1785 he published a *Theory of the Earth* in the first volume of the Transactions of the Royal Society of Edinburgh. Encouraged to seek observations to support his theory, he found several telling examples, enabling him in 1795 to expand his ideas into a two-volume book: *Theory of the Earth with Proofs and Illustrations*. His friend, John Playfair, brought Hutton's ideas to a wider audience in *Illustrations of the Huttonian View of the World*, published in 1802.

Hutton popularised the notion that '*the present is the key to the past*'[6]. As he put it in his book, '*In examining*

Earth's Climate Evolution, First Edition. Colin P. Summerhayes.

Figure 2.1 *James Hutton.*

things present, we have data from which to reason with regard to what has been'[6]. In following that approach, Hutton echoed Isaac Newton's dictum that '*We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances*'[6]. But that's not all. Hutton went on to say, '*and, from what has actually been, we have data for concluding with regard to that which is to happen hereafter*'[6]. Here was an extraordinary notion – that examples from the past preserved in the geological record could provide examples of what might happen on Earth in future if the same guiding conditions were repeated.

Observing the processes at work on his farm and in the surroundings, Hutton saw that today's hills and mountains are far from being everlasting. They were sculpted by the slow forces of erosion. The eroded materials were transported by rivers and dumped in the ocean, where they accumulated to great thickness before being raised into mountains. The process then began again, in yet another great geological cycle. Hutton's idea that the ruins of earlier worlds lay beneath our feet was demonstrated by younger and undisturbed strata resting uncomfortably on older folded and eroded beds, notably at Siccar Point on Scotland's east coast. To some degree, Hutton's concept repeats ideas proposed originally in the notebooks of Leonardo Da Vinci in about 1500[7]. Perhaps this is an early example of the convergent evolution of ideas. The slowness of geological processes led Hutton to conclude that Earth's history was unimaginably long. Indeed, in dramatic contrast to biblical scholars, he found that Earth's history showed '*no vestige of a beginning, – no prospect of an end*'[6].

He was wrong in one respect: not all operations of nature are equable and steady. Earthquakes and volcanic eruptions are sudden, as are meteorite strikes of the kind that cratered the surface of the moon. Even so, he realised that earthquakes and volcanic eruptions, although discontinuous, are recurrent. Neither he nor many other savants of his time knew about the kind of catastrophic meteorite impact that we now believe led to the great extinction and loss of the dinosaurs 65 Ma ago.

When Buffon died, Georges Cuvier (1769–1832) (Figure 2.2) took his place as France's leading natural historian. Cuvier was a key figure in establishing the scientific fields of comparative anatomy and palaeontology. He was elected a member of the Academy of Sciences in 1795, professor of natural history at the College de France in 1799 and professor at the Jardin des Plantes in 1802. He also became a foreign member of the Royal Society of London in 1806 and was ennobled Baron Cuvier in 1819.

Cuvier used his knowledge of anatomy to identify fossil species and their likely interrelationships. While Buffon thought that Siberian fossils of woolly rhinoceros and elephant were the remains of animals still living, Cuvier showed that they were extinct, and identified the elephant remains as mammoths[3]. Both men knew that these animals were found frozen into the tundra '*with their skin, their fur and their flesh*'[8,9]. Unlike Hutton, Cuvier was keen on the moulding of geological history by catastrophic events.

Figure 2.2 *Georges Cuvier.*

He thus attributed this freezing to an environmental catastrophe: '*this event took place instantaneously, without any gradation … [and] rendered their country glacial*'[3, 10]. Here we have the first inkling of the idea of the Ice Age.

Cuvier's senior colleague Jean-Baptiste de Monet, Chevalier de la Marck, commonly known as Lamarck (1744–1829), challenged his call for catastrophic change. Studying the sequence of fossil molluscs from the region around Paris, he concluded in 1802 that many of them belonged to genera that are now tropical and that they represented a slow change of climate with time[3].

At about the same time, in the late 1790s, William Smith (1769–1839), a land surveyor engaged in building the network of canals that now cross the English countryside, began using distinctive fossils to identify and map the occurrence of particular strata. This led him to publish in 1801 a 'prospectus' for the production of a geological map of England,[3] something he achieved in 1815. He had invented the science of 'stratigraphy' – the use of fossil remains to establish the succession of strata – which now underpins our appreciation of changes in climate through geological time.

French geoscientists were quick to seize upon this new approach to geohistory. In 1802, Alexandre Brongniart (1770–1847), the newly appointed young director of the porcelain factory at Sèvres, near Paris, visited England to find out more about the mass production of ceramics by the Wedgwood factory[3]. In London, he dined with fellows of the Royal Society, where is likely to have become aware of the novel ideas and unpublished maps of William Smith. Searching for new deposits of clay, and working with Cuvier to identify fossils, Brongniart began a systematic survey of the Parisian region. Much like Smith, Brongniart and Cuvier used fossils to determine the order of the layers of sedimentary rock of the Paris Basin and map the outcrops of the strata. They concluded that the area had been submerged at times by the sea and at times by freshwater – a first indication that environmental conditions could change with time in a relatively small area, and something that went beyond anything attempted by Smith in its high level of detail. In 1808, they delivered a preliminary report of their paper on the Paris Basin, with an accompanying draft geological map that was eventually published in 1811[3].

Brongniart and Cuvier were not the first to map the sedimentary divisions of the Paris Basin. The famous French chemist Antoine-Laurent Lavoisier (1743–1794), who had discovered oxygen and hydrogen, and was guillotined during the French Revolution, beat them to it. Lavoisier's 1789 memoir on the topic[11] was brought to light by sedimentologist Albert Carozzi of the University of Illinois in 1965[12]. Lavoisier saw in the alternating deep- and shallow-water (littoral) deposits of the Paris Basin evidence for a succession of transgressions (floodings) and regressions (retreats) of the sea. His vision of how these packages of sediment were built up through time by the alternating rising and falling of sea level is like the modern understanding of the origin of sedimentary cycles. It involved '*a very slow oscillatory movement of the sea … [each oscillation] requiring several hundred of thousand years for completion*'[11, 12]. Lavoisier's cross-sections of the Basin provide an outline for the correct classification of its Tertiary deposits. He was a man far ahead of his time.

These parallel French and English efforts were major developments in the evolution of palaeontology and geology. They provided an essential platform for the development of palaeoclimatic studies and influenced the thinking of those who followed.

Along with Cuvier, one of the most influential scientific men in Europe in the early 1800s was the German naturalist Baron Alexander von Humboldt (1769–1859) (Figure 2.3, Box 2.1)[13–18]. By 1797 Humboldt was planning an overseas expedition, learning to use a wide range of scientific and navigational instruments, and visiting experts in Vienna and Paris. While in Paris, Humboldt met the botanist Aimé Bonpland (1774–1854), who was to be his travelling companion. Humboldt focused on physical geography, geology, geomorphology and climatology, while Bonpland focused on flora and fauna. Visiting Madrid, they obtained royal assent to scientifically examine Spain's American territories as a contribution to understanding the physical make-up of the world. They sailed from La Coruña on 5 June 1799 and visited South and Central America, the West Indies and the United States, returning to France in August 1804. The major scientific outcomes were Humboldt's seminal *Essay on the Geography of Plants*, published in 1805, and his treatise on *Isotherms and the Distribution of Heat over the Earth's Surface*, published in German in 1816. Wider recognition followed publication of his more general works: *Views of Nature* in 1808 and the travelogue *Personal Narrative of a Journey to the Equinoctial Regions of the New Continent* in three volumes in 1814, 1819 and 1825. Further travels, to Russia and Siberia, in 1829 led to the publication of *Fragments of the Geology and Climatology of Asia*

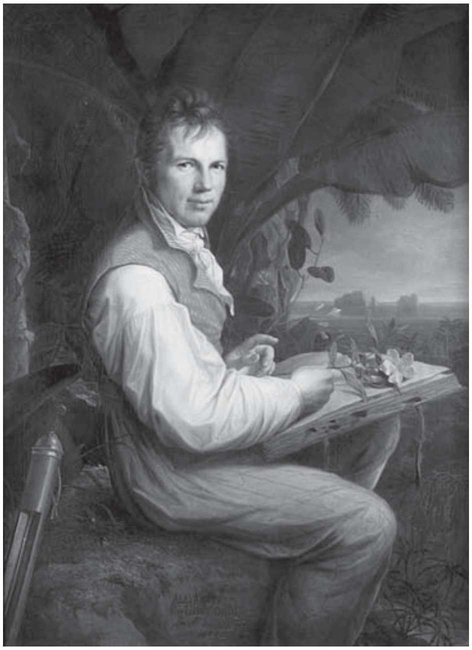

Figure 2.3 *Alexander von Humboldt working on his botanical specimens.*

in 1831. These works laid the foundations for the study of physical geography, biogeography, meteorology and climatology.

Box 2.1 Baron Alexander von Humboldt.

Humboldt was born in Tegel, now the location of Berlin's major airport. At the age of 19, he developed a lifelong interest in botany, whcih led him to investigate the laws that govern not only the diversity of plant life, but also everything that impinged on the environment. Entering the University of Göttingen to study natural sciences in 1789, he travelled to Mainz to meet Georg Forster, the naturalist from Captain Cook's second voyage. Forster encouraged Humboldt to study the basalts of the Rhine, a topic that Humboldt wrote up in his first book, in 1790. Next year, the two men travelled to England together, visiting Sir Joseph Banks, who had been the naturalist on Cook's first expedition, and Captain William Bligh, who had been on Cook's third. These encounters gave Humboldt a desire to travel and study regions not yet explored scientifically and – like Forster – to combine science and travel writing. In England, he met the physicist Henry Cavendish, who introduced him to the work of Antoine Lavoisier. Humboldt's study of Lavoisier convinced him of the importance of measurement and experimentation and of the value of scientific cooperation and the exchange of ideas. Scientific networking is not new. In June 1791, Humboldt joined Freiburg's School of Mining, run by one of the great men of geological science, Abraham Gottlob Werner (1750–1817)[19]. Werner led the so-called Neptunists, who thought that all rocks were once precipitates in the ocean. Humboldt initially followed Werner on this, for example in his work on the Rhine basalts, but eventually joined the so-called Vulcanist or Plutonist school led by James Hutton, who showed that granites were created from molten rock. Despite his mining studies, Humboldt found time to continue research on plant life, winning the Saxon gold medal for his work. In 1792, aged 22, he joined the Prussian Mining Service, rising to become inspector of mines. During his early twenties, Humboldt dreamt of writing a *Physique du Monde*, a total description of the physics of the world. His dream would come to fruition in his five-volume work *Cosmos: A Sketch for a Physical Description of the Universe*, starting with a first volume in 1845. In recognition of his outstanding contributions, many geographical features are named after him, including the Humboldt Current off the coast of Peru, as well as numerous towns, forests, streets, parks, universities, colleges and schools, a lunar crater and several plants and animals. Humboldt was awarded the Copley Medal by London's Royal Society in 1852.

Humboldt's view of nature was holistic. He saw that its parts were intimately related and were only understandable with reference to the whole, with plants growing where they did in response to relationships between biology (plants, animals and soils), meteorology (temperature, winds, humidity and cloudiness), geography (altitude, latitude and distance from coast) and geology.

2.2 Charles Lyell, 'Father of Palaeoclimatology'

The ideas of Buffon, Hutton, Humboldt, Cuvier and Brongniart had a considerable influence on a young Scottish geologist, Charles Lyell (1797–1875) (Figure 2.4, Box 2.2). Lyell was famed for turning Hutton's big idea into a fundamental geological principle that has stood the test of time, albeit with certain modifications. He was destined to become the greatest geologist of his age[20, 21]. It seems oddly fitting that he was born in 1797, the year that Hutton died.

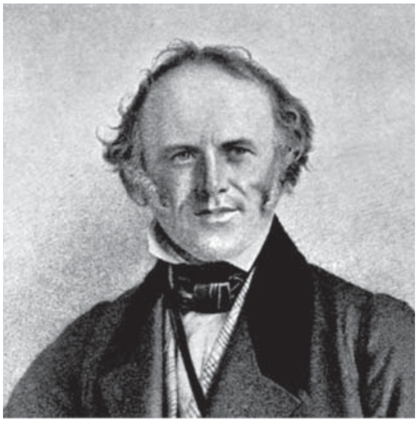

Figure 2.4 *Charles Lyell.*

Box 2.2 Charles Lyell[20, 21].

Born at Kinnordy, near Dundee, Scotland, Lyell was brought up at Bartley Lodge in England's New Forest. The son of a wealthy naturalist after whom the plant *Lyellia* was named, he was fascinated by natural history. Studying classics at Oxford between 1816 and 1819, he attended lectures in geology given by William Buckland. Deciding to become a lawyer, he entering Lincoln's Inn in London in 1820, but his interests drew him into the emerging science of geology. Lyell rose to fame with the publication of his *Principles of Geology* in three volumes between 1830 and 1833. This was the first comprehensive geological textbook. Its 12th edition was published in 1875, just after his death. His reputation was further enhanced by the publication in 1838 of a companion volume, *Elements of Geology*. Originally intended as a supplement to the *Principles*, this formed an independent practical guide to the new science of geology. Together, the two books put the study of geology on a firm footing. Lyell's influence was further assured with his naming of a number of geological periods: the Recent (now the Holocene), the Pleistocene, the Pliocene, the Miocene and the Eocene. From 1831 to 1833, Lyell was the first professor of geology at London's fledgling Kings College, but he later earned his living as a geological writer. His influence stretched far and wide, through publications, lectures and his association with the Geological Society of London. Having been elected a fellow of the Society in 1819, and after publishing his first paper there in 1823, he became one of its joint secretaries from 1823 to 1826, its foreign secretary from 1829 to 1835, a vice president for 20 sessions and its president in both 1835–37 and 1849–51. His talent was recognised early. He was elected a fellow of the Royal Society in 1826 and received its Copley Medal in 1858. The Geological Society awarded him its Wollaston Medal in 1866. Recognising his huge contribution to understanding of the Earth, he was knighted by Queen Victoria in 1848, at the age of 51, and made a Baronet in 1864. The year he died, the Geological Society inaugurated the prestigious Lyell Medal. Lyell has a crater on the Moon and a crater on Mars named after him, along with an Antarctic glacier and several mountains. He was buried in Westminster Abbey, an honour reserved for few scientists. His burial memorial reports that, '*For upwards of half a century he has exercised a most important influence on the progress of geological science, and for the last twenty-five years he has been the most prominent geologist in the world.*'

The key to Lyell's understanding of the Earth lies in the subtitle to his *Principles of Geology*, namely '*An attempt to explain the former changes of the Earth's surface by causes now in operation*', which demonstrates the influence of Hutton on his thinking. Lyell's conception that the same natural laws and processes that operate in the universe now have always operated, and that they apply everywhere, was later named 'uniformitarianism' by William Whewell (1794–1866). In effect, Lyell took Hutton's ideas and magnified them a hundredfold, showing how they applied to the many different aspects of geology, from fossil life to volcanoes. In doing so, he was labouring to overcome the catastrophist theories of scientists like Cuvier. Lyell believed that what appeared from the geological record to be the results of catastrophic events could instead have arisen through the slow and steady action of processes observable today. Like Hutton, he thought immense periods of time were required to wear down the land and deposit the sediments eventually represented by various uplifted strata. This would not endear him to strict interpreters of Genesis.

Lyell drew heavily on contemporary geological literature to produce the *Principles*[20–22]. Particularly influential was *Conchiologia fossile subapennina* (*The Fossil Seashells of the SubAppenines*), published in 1814 by the Italian geologist Giovanni Battista Brocchi (1772–1826), curator of the Museum of Natural History in Milan[3, 22]. Lyell was fascinated by Italy. Besides honeymooning there, he studied the geology with local guides, read the Italian literature and met local specialists. He may have read Brocchi's work in Italian, or else the English translation made in 1816 from a copy given to William Buckland during a visit to Milan in that year[23].

An expert on the fossil seashells of the Apennines, Brocchi used the change in the percentage of living forms in fossil assemblages with time as a means of dating relatively their encasing formations. Using this approach, he produced a definitive study of the historical geology of Italy, an advance comparable to that made by Smith in England and Brongniart and Cuvier in France. Comparing modern and ancient molluscs, he noticed that the recent species of older Tertiary strata now inhabit warmer climates, suggesting, much as Lamarck had seen in the Parisian region, that the world was cooling. Lyell took note both of the approach and its conclusion.

Young Lyell hoped to meet Cuvier during his first visit to the continent on a tour with his family in June 1818. Cuvier was away, however, so Lyell peeked into his office, looked at some of his fossil specimens and read his paper on the 'Geology of the Country around Paris'. He went on to climb the glaciers around Chamonix and the Grindelwald glacier in Switzerland, which gave him an inkling of the power of ice. This was the first of many visits to all parts of the United Kingdom, to much of Europe and to North America, which would make him the best-travelled of the geologists of his generation. Seeing the most rocks is one route to becoming an excellent geologist, and Lyell saw plenty. Equally important is becoming fully submerged in the world of ideas about the subject, which Lyell managed by meeting and corresponding with all of the major geological figures of his time in Europe and North America.

Lyell eventually met Cuvier, along with Brongniart and Brongniart's former student Constant Prévost (1787–1856), when visiting Paris in 1823 to improve his French[20]. He was impressed to find that young Prévost, unlike Cuvier, thought that the changes in strata in the Paris Basin had come about gradually, not as the result of a series of catastrophic events. Others, like Karl von Hoff (1771–1837) in Germany, also concluded that, given enough time, ordinary agencies could effect major changes. Over the years, Lyell and Prévost worked closely together, recognising strong similarities between the Mesozoic strata of Normandy and of southern England.

Lyell became expert at identifying fossil molluscs. By 1828, following Brocchi, he had used the percentages of modern molluscs in each epoch, and the relations of strata to one another, to subdivide the Tertiary Period into several geological Epochs. This statistical approach was a novelty at the time. Perhaps Lyell was following Humboldt's dictum that all science should be based on numbers. The following year, he met Gérard Deshayes (1795–1875), a French palaeontologist with an even larger collection of fossil molluscs, who had arrived at similar views. He persuaded Deshayes to expand on his work and combine it with Lyell's own, publishing the results in the *Principles*, where he named the four periods of the Tertiary as the Eocene ('dawn of the recent', with 3.5% modern species), Miocene (with 17% modern species), Early Pliocene (with 35–50% modern species) and Late Pliocene (with 90–95% modern species).

Later, Lyell worked closely with the Danish palaeontologist Henrick Beck (1799–1863) to extract yet more information from fossil molluscs, finding that Europe's Eocene had a tropical climate, its Pliocene had a climate more like today's and the Miocene lay in between. In Chapter 10 of Volume 2 of the *Principles*, he established that there was '*a great body of evidence, derived from independent sources, that the general temperature has been cooling down during the epochs which immediately preceded our own.*' Later palaeobotanical work confirmed this. Large pointed leaves with many stomata and thin cuticles typical of warm humid climates characterised Europe's early Tertiary and the tropical rainforest flora of the Eocene London Clay[24].

Lyell was much influenced by Humboldt, whom he met in Paris in 1823 and again in Potsdam in 1850. He was particularly taken with Humboldt's holistic view of nature and his observations of the way in which the distribution of plants reflected both the geography and the climate. Lyell was also among the first to appreciate the geological significance of Humboldt's 'isothermal lines': lines of equal temperature that could be used to divide the world into climatic zones[14]. Observing that the positions and sizes of continents and the development of mountain ranges distorted those lines and climatic zones, he made a crucial intellectual leap: recognising that that many of Europe's older rocks had been deposited in much warmer climates than today's, he deduced that if the Earth's climate zones had not changed, then the land must have moved – the geography must have changed with time (Figure 2.5). Writing to Gideon Mantell (1790–1852) in February 1830, and swearing him to secrecy, he said, '*I will give you a receipt [i.e. recipe] for growing tree ferns at the pole, or if it suits me, pines at the equator; walruses under the line [the Equator], and crocodiles in the arctic circle*'[25]. This exciting new idea profoundly changed the way people thought about the distant past.

Lyell acknowledged his debt to Humboldt in a letter to his geological friend George Poulett Scrope (1797–1876): '*Give Humboldt due credit for his beautiful essay on isothermal lines: the geological application of it is mine, and the coincidence of time 'twixt geographical and zoological changes is mine, right or wrong*'[25]. Would his theory hold the test of time? In the same letter, Lyell confessed '*That all my theory of temperature will hold, I am not so sanguine as to dream. It is new, bran new [at that time, the term 'bran new' was interchangeable with 'brand new']*'[25].

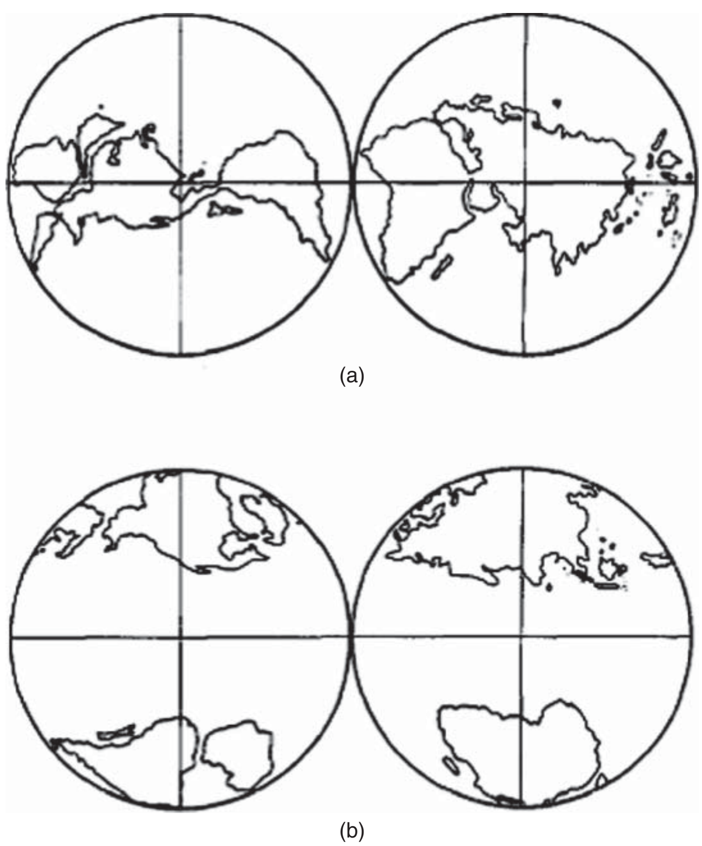

Figure 2.5 *Lyell's attempt to show how changes in the positions of the continents through time might contribute to extremes of (a) heat or (b) cold.*

I focus on Lyell because he was the first scientist to concentrate intently on the geological record of past climates, and it would be fair to call him the 'father of palaeoclimatology'. He devoted three chapters of Volume I of the *Principles* to showing how the climates of past times could be recognised from the types and distributions of sedimentary rocks and their enclosed fossils – especially the seashells he so enjoyed studying. Not only that, but he also incorporated seven chapters on 'aqueous causes', under which he listed rivers, torrents, springs, currents, tides and icebergs as agents of change in the inorganic world, all of which were likely to change as climate did. Lyell began his climate chapters by recapping the approach he took in a scientific paper in 1825–26, where he deduced the likely conditions of deposition of fossil freshwater limestones[26]. His chapters on climate rehearsed the standard arguments for climate change from fossil evidence. He agreed with Buffon, Cuvier and Brocchi that the fossil evidence showed that Europe's climate was much warmer in former times. Unlike Cuvier, he found no need for some catastrophe to explain the cooling, and, like Fourier, he thought Buffon wrong to suggest that this was due to the solid Earth having been hotter in former times.

Lyell's thinking on the geographical control of climate matured as he gathered more data – especially from his visits to North America in the 1840s. For example, in the 12th edition of his *Principles*, published in 1875, anticipating later notions of the break-up of formerly continuous continents, he observed that '*If we go back ... to the Eocene period ... we find such a mixture of forms now having their nearest living allies in the most distant parts of the globe, that we cannot doubt that the distribution of land and sea bore scarcely any resemblance to that now established*'[27]. Along the same lines, he noted that '*In the case of the great Ohio or Appalachian coal-field ... it seems clear that the uplands drained by one or more great rivers were chiefly to the eastward, or occupied a space now covered by the Atlantic Ocean*'[27]. Nothing he had discovered in 45 years of publishing the *Principles* detracted from his conclusion that '*Continents therefore, although permanent for whole geological epochs, shift their positions entirely in the course of ages*'[27]. He was well aware of how geography – manifested as the positions of continents, their coasts and their topography – modified climatic zones, observing that, '*on these geographical conditions the temperature of the atmosphere and of the ocean in any given region and at any given period must mainly depend*'[27].

Moving the continents around was dramatic stuff at the time, and, unfortunately for Lyell, he had no other information than his climate theory to back him up. It would be left to others to prove him correct as more data arrived. In due course, Lyell's uniformitarian assumption that the Earth's average temperature had remained more or less constant through time would be proved wrong, but many of his other assumptions about climate remain valid, including the notion that the continents had changed position through time.

Lyell broke with tradition in abandoning the theory in vogue in the early 19th century, and embraced by – among others – his old Oxford tutor, William Buckland (1784–1856) (Figure 2.6), that the erratic blocks of rock littering the British landscape were the relics of Noah's flood. Like Hutton, Lyell was keen to take the scripture out of geology and the geology out of scripture. Buckland's attempts to relate geology to scripture are hardly surprising, given that he was an Anglican clergyman. An influential man, he was twice elected president of the Geological Society, in 1824–26 and 1839–41. But he had an open mind, and eventually abandoned the 'deluge' hypothesis.

Just as Humboldt had influenced Lyell, so Lyell too influenced a younger man with a big future, Charles Darwin (1809–1882), who took Volume 1 of Lyell's *Principles* with him when he sailed in late 1831 on his scientific voyage around the world on HMS *Beagle*. Darwin became a fellow of the Geological Society of London

Figure 2.6 *William Buckland.*

in 1836, and, like Lyell, served the Society as an officer, being a member of council from 1837 to 1850, one of the two joint secretaries from 1838 to 1841 and a vice president from 1844 to 1845. Like Lyell, he was made a fellow of the Royal Society, was awarded the Geological Society's Wollaston Medal (1859), was awarded the Royal Society's Copley Medal (1864) and was buried in Westminster Abbey.

Lyell's notion of significant change arising from slow processes operating steadily over the eons of geological time provided Darwin with the long periods through which tiny natural variations, which we now understand as genetic mutations, could accumulate and give rise to different species through natural selection. The two men met in October 1836, shortly after Darwin's return, and became friends. Lyell nominated Darwin to the Council of the Geological Society, and later helped to ensure that on 1 July 1858 Darwin's paper on natural selection was read at the Linnaean Society in London, alongside that of Alfred Russell Wallace, who had reached the idea independently. Darwin was also influenced by Humboldt, whom he met in London in 1842. As Richard Holmes pointed out in 2008 in *The Age of Wonder*, '*Science is truly a relay race with each discovery handed on to the next generation … and the world of modern science begins to rush towards us*'[28].

Lyell's *Principles* considerably influenced thought in Victorian times. As James Secord points out in his introduction to the Penguin Classic version in 1997, the *Principles* was '*a manifesto for fundamental change in the organisation of intellectual life*', capping the campaign by Lyell and others '*to sever all links of geology to a theology based in scripture*'[29]. After Lyell, geologists no longer accepted the biblical flood as having any worth in analysing Earth's history. For a modern view of Lyell's merits, we may turn to *Time's Arrow, Time's Cycle*, the 1987 work by palaeontologist Stephen Jay Gould, for whom Lyell '*doth bestride my world of work like a colossus*'[30].

Nevertheless, the *Principles* had its flaws. For example, the first volumes, published in 1830–32, did not mention the Ice Age. Like James Hutton, Lyell knew that mountain glaciers transport rock debris, which is dumped in piles called moraines where the glaciers melt, and that rivers sweep the glacial sand and mud away to the sea. But he also knew that polar mariners had seen drifting icebergs transporting large amounts of rock (Figure 2.7). This observation led him to speculate that melting icebergs would dump their loads on the seabed to '*offer perplexing*

(a)

Figure 2.7 *Ice transporting rocks at sea: (a) stranded iceberg carrying a load of rocks in the Fridtjof Channel, Antarctic Peninsula; (b) ice floe carrying a load of rocks in the Erebus and Terror Gulf, Antarctic Peninsula.*

(b)

Figure 2.7 *(continued)*

problems to future geologists'[27]. In Volume 3 of the first edition of the *Principles,* he speculated that the huge erratic blocks of rock littering the landscape in the Alps and the Jura had been transported by floating ice, not by ice sheets sliding over land, as some Swiss geologists thought at the time. At that time, he did not connect the erratic blocks littering the Swiss landscape with those of the United Kingdom.

2.3 Agassiz Discovers the Ice Age

One great mind is never enough – it requires many for us to get to grips with how the world works. And so it was left to another geological genius, Jean Louis Rodolphe Agassiz (1807–1873) (Figure 2.8, Box 2.3), to point out how important ice may have been in the geological history of Europe and North America.

Like Lyell, Agassiz upset the comfortable world of established thought. In the summer of 1837, he turned the world of geological ideas upside down with a proposal made at the annual meeting of the Swiss Society of Natural Sciences, of which he was the new president: he thought a vast ice sheet must have carried erratic blocks across Europe in a recent Ice Age. Living in Switzerland, he knew that far from the snouts of glaciers, the rock surfaces were

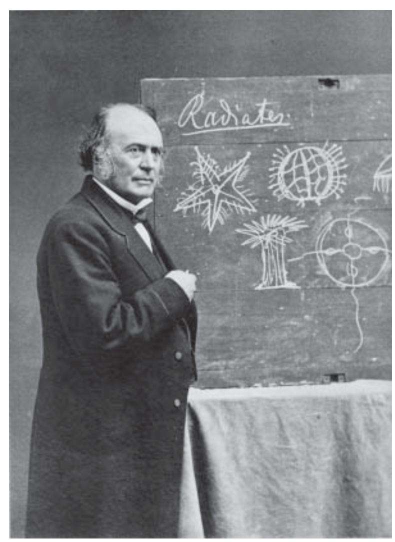

Figure 2.8 *Louis Agassiz drawing radiates, 1872.*

Box 2.3 Jean Louis Rodolphe Agassiz.

Agassiz was born in Switzerland in 1807. He studied medicine and natural sciences at Zurich, Heidelberg and Munich before moving to Paris, where he studied with Humboldt and Cuvier. In 1832, he was appointed professor of natural history at Neuchatel in the Swiss Jura. He published five volumes of research on fossil fish between 1833 and 1843. In 1846, he visited the United States and was invited to stay there, becoming head of the Lowell Scientific School of Harvard University in 1847. Harvard made him a professor of zoology and of geology, and he founded the Museum of Comparative Zoology there in 1859, serving as its director until he died. He was awarded the Geological Society of London's Wollaston Medal in 1836 for his work on fossil fish, and was elected one of the Society's foreign fellows in 1841. He thought highly of Charles Lyell, and named an ancient jawless fish after him: *Cephalaspis lyelli*, which lived in Scottish lakes in Old Red Standstone times in the Silurian and late Devonian Periods between 420 and 360 Ma ago. Like Lyell, Humboldt and Darwin, Agassiz became one of the world's best-known scientists of the 1800s. Mountains, glaciers and a Martian crater are named after him, as are several fish and beetles, a fly and a tortoise. A fossil glacial lake is also named after him, as is the Agassiz Glacier in the United States' Glacier National Park.

scratched and smoothed, and strewn with boulders and rubble like that still being carried and deposited by the ice. His new idea countered the suggestion of the first scientific explorer of the Alps, Horace Bénédicte de Saussure, in the late 1700s, that fast rushing streams deposited these boulders in catastrophic events. Hutton disagreed with Saussure, proposing in his 1795 *Theory of the Earth* that a former extension of Swiss glaciers accounted for the distribution of boulders of Mont Blanc granite, which de Saussure attributed to a deluge. Hutton wrote, '*There would then have been immense valleys of ice sliding down in all directions towards the lower country, and carrying large blocks of granite to great distance, where they would be variously deposited and many of them remain an object of admiration to after ages, conjecturing from whence or how they came*'[6].

Later Swiss observers agreed with Hutton. In 1818, Jean Pierre Perraudin, a guide and chamois hunter, interpreted the gouges in hard unweathered rock as indicating the former widespread extent of Alpine glaciers. His remarks came to the attention of Ignace Venetz, chief engineer for the Swiss Canton du Valais, who in 1821 deduced from the positions of old terminal moraines downslope from present glacier terminations that the climate had warmed and the glaciers shrunk. He presented this finding to the annual meeting of the Swiss Society of Natural Sciences in 1829, suggesting that glaciers had once extended over the Jura and into the European plain. Jean de Charpentier (1786–1855), director of mines of the Canton de Vaud, applied Venetz's observations more widely, proposing to the annual meeting of the same Society in 1834 that widespread erratic blocks and moraines had been deposited by ice – Swiss glaciers had formerly been much more extensive.

Agassiz, who attended Charpentier's lecture, had been one of his students. A trip into the field with Charpentier in 1836 to study the evidence for glacial transport convinced him. We'll let Elizabeth Agassiz tell us about her husband's ensuing lecture to the same Society in 1837: '*In this address he announced his conviction that a great ice-period, due to a temporary oscillation of the temperature of the globe, had covered the surface of the earth with a sheet of ice, extending at least from the north pole to Central Europe and Asia … "Siberian winter," he says, "established itself for a time over a world previously covered with a rich vegetation and peopled with large mammalia, similar to those now inhabiting the warm regions of India and Africa. Death enveloped all nature in a shroud, and the cold, having reached its highest degree, gave to this mass of ice, at the maximum of tension, the greatest possible hardness". In this novel presentation the distribution of erratic boulders, instead of being classed among local phenomena, was considered "as one of the accidents accompanying the vast change occasioned by the fall of the temperature of our globe before the commencement of our epoch" … This was, indeed, throwing the gauntlet down to the old expounders of erratic phenomena upon the principle of floods, freshets, and floating ice*'[31].

Much astonishment and not a little ridicule greeted Agassiz's proposal that an ice sheet like that now covering Greenland formerly covered much of northwest Europe as far south as the Mediterranean. The great German geologist Leopold von Buch (1774–1853) attended the meeting and could hardly conceal his indignation and contempt for this young upstart[31]. It was von Buch who had first identified the erratic blocks littering the north German plain as having come from Scandinavia, by some unknown means. Even Humboldt, who knew Agassiz from the time they had spent together in Paris, counselled his young friend to abandon '*these general considerations (a little icy besides) on the revolutions of the primitive world – considerations which, as you well know, convince only those who give them birth*'[31].

Some of the reluctance to accept Agassiz's idea stemmed from the fact that very few European scientists knew anything about the extent of ice sheets. The vast extent of the Antarctic ice sheet would not be fully appreciated until after the visits to the Ross Sea and Ross Ice Shelf with HMS *Erebus* and HMS *Terror* in 1841 and 1842 by James Clark Ross (1800–1862), whose book on his expedition was not published until 1847. The icy mass of East Antarctica had been only glimpsed before, by Von Bellingshausen in 1820 and by Dumont d'Urville and Charles Wilkes in 1840. It was not even known that a vast continuous ice sheet covered Greenland. Even so, Agassiz had leapt ahead of himself by claiming that ice extended as far as the Mediterranean, when glacial erratic blocks were actually confined to the Alps and northernmost Europe.

Undeterred, Agassiz wrote up his ideas for an English-speaking audience in a short paper published in 1838[32], in which he set out the evidence for glacial activity, and noted that grooved and polished rocks beneath Swiss glaciers are usually overlain by fine sand, followed by rounded pebbles and then by angular blocks – the opposite of the sequence expected from transport by currents. The fine sand came from the disintegration of rock fragments and most likely caused the polishing. He called for research to see whether this same relationship applied in the polar regions.

Agassiz pulled his theories together in his 1840 book *Etudes sur les Glaciers*[33], using the distribution of boulders that could only have been transported by ice and the gouges in the smoothed surfaces of rocks over which glaciers had passed, along with other features, to divine the former existence of ice sheets and glaciers where none now existed, and even to propose that ice sheets could move erratic blocks up hill, for example to the top of the Jura Mountains near his university, where the 3000 ton *Pierre-a-Bot* (toadstone) occurred. Charpentier published his own *Essay on the Glaciers and the Erratic Terrain of the Rhone Basin* in 1841. His Swiss-scale vista was eclipsed by Agassiz's Europe-wide vision, which became global after his arrival in North America in 1846, where he discovered further evidence for former ice sheets. Agassiz started a major research programme on Alpine glaciers, spending a decade working at an alpine research station and climbing all over the Alps with fellow researchers and students, literally starting the study of glaciology. He published the results in 1847 in *Système Glaciare*.

Agassiz was keen to convert William Buckland, the leading proponent of the biblical deluge hypothesis for explaining erratic blocks. Buckland was intrigued enough by Agassiz's theory to visit Switzerland and see the evidence. Becoming convinced that Agassiz might be right, he invited Agassiz to visit Britain to see whether evidence of a past ice sheet could be found there too. Agassiz duly arrived on this mission in August 1840, visiting Scotland and lecturing on his new theory at the meeting of the British Association for the Advancement of Science in Glasgow. Lyell attended the meeting, but remained unconvinced.

Touring Scotland and other parts of Britain, Agassiz and Buckland found the evidence they were looking for: moraines, erratic blocks and polished and grooved rocks showed that great sheets of ice like that covering Greenland must formerly have covered the mountainous areas of Great Britain. Buckland even managed to convince Lyell that the piles of rocks near Lyell's Scottish home were moraines deposited at the edge of this former ice sheet[34]. In November and December 1840, Agassiz, Buckland and Lyell gave lectures at the meetings of the Geological Society of London on their discoveries of evidence for former British ice sheets[37]. The initial reaction was hostile[25]. Buckland concluded the 1840 meeting in high spirits by condemning to '*the pains of eternal itch without the privilege of scratching*'[36] anyone who challenged the evidence supporting the Ice Age theory. But although the papers were read at the Society's meetings, and précis were published by the Society's secretaries to convey the main points to the readers of the Society's Proceedings, the full papers were never published[34]. Part of the problem was that another Scottish lion of the British geological scene, Roderick Murchison (1792–1871), who had visited Scotland with Agassiz and Buckland, was unconvinced. Murchison had been president of the Geological Society in 1831–33, and was again in 1841–43. During his presidential address to the Society in the latter term, he chose to attack the Ice Age theory. He did not back away from this stance until 1862, when he finally recanted in an address to the Geological Society of London. Sending a copy of his 1862 paper to Agassiz, he wrote: '*I have the sincerest pleasure in avowing that I was wrong in opposing as I did your grand and original idea of my native mountains. Yes! I am now convinced that glaciers did descend from the mountains to the plains as they do now in Greenland*'[37]. The evidence had mounted.

In his 1840 paper[37], Agassiz explained that rivers draining the massive ice sheet that had brought the erratic boulders to the plains of northern Europe had also given rise to widespread outwash gravels, for which there was no other explanation. The existence of this ice sheet indicated that a period of intense cold – an Ice Age – had intervened between the warm conditions of the Tertiary period and those of today. Modern mountain glaciers were the remnants of that former ice sheet. Having found polished rocks, erratic blocks and outwash gravels across much of Scotland, Ireland and the north of England, along with rounded hillocks of ice-cut rock named '*roches moutonnés*', he deduced that an ice sheet had covered these areas too. The distribution of erratic blocks suggested that they had moved in all directions away from 'centres of dispersion', which would not be expected for deposition from floating ice. The main centres of dispersion in the British Isles were the mountains of Ben Nevis, the Grampians, Ayrshire, the English Lake District, Wales, Antrim, Wicklow and the west of Ireland. Floating ice from Scandinavia explained the origin of erratic blocks on the east coast of England.

2.4 Lyell Defends Icebergs

Lyell met Charpentier in 1832 in Switzerland, while on his honeymoon, and so was exposed to Charpentier's ideas[20]. He also met Agassiz several times during the 1830s, and they worked together on fossil fish for a while[20]. They met again when Agassiz visited Buckland in 1840, and together presented their papers on glaciers to Geological Society meetings late that year. But Lyell was a hard man to convince, and the extent to which he accepted the notion that sheets of ice had transported boulders was distinctly limited. Having seen moraines in the Alps, he was not going to deny the role of mountain glaciers in transporting erratic blocks. But – what happened beyond the mountains? Lyell thought icebergs had done the work.

Lyell used the word 'till', a Scottish farmers' term, to describe the widespread unstratified jumbled mass of erratic blocks, pebbles and clay covering parts of the British Isles, and which we now call 'boulder clay'. He lumped 'till' together with other deposits from the glacial era (like Agassiz's outwash fans of gravel) into what he called the 'glacial drift', a term chosen on the one hand to support his iceberg theory and on the other to replace the former term 'diluvium', which came from the biblically inspired 'flood' hypothesis formerly used to explain the distribution of this recent debris[20].

Agassiz was unable to explain in detail the origin of till, but assumed that it was derived from the ice sheet in some way, not least because the boulders in the till were typically striated and gouged like ice-transported rocks. He imagined that boulders now found as erratic blocks might have slid down the Alpine slopes and out across his proposed European ice sheet in some catastrophic fashion, to be left behind when the ice beneath them melted. Lyell, in contrast, offered a noncatastrophic 'steady-state' mechanism: the supply of rocks, pebbles and rock flour from floating icebergs. We now know more than both Lyell and Agassiz. The fine-grained clayey element of 'boulder clay' is rock 'flour' or powdered rock, derived from rock fragments interacting with each other and with the surrounding country rock as ice sheets move over the ground.

In his 1840 paper, Lyell suggested that '*the assumed glacial epoch*'[37] had arisen as Scottish glaciers first advanced to the sea, as they did in South Georgia, then remained stationary while the intervening hollows filled with snow and ice, on which boulders slid to their present positions – much as Agassiz was suggesting for the erratic blocks of western Europe. The ice then retreated, leaving moraines and debris behind. To explain the origin of boulder clay or till away from mountainous areas where glaciers could provide a means of transport, Lyell called, as he had in his *Principles*, on the transport of rocks and sediment by floating ice[37]. He rejected Agassiz's idea that some catastrophic event had caused boulders to fall off the Alps and slide out over the European ice sheet, because he believed that the Alps rose gradually, in consistency with his uniformitarian principles.

Although he was exposed back in 1832 to Charpentier's observation that Swiss glaciers moved boulders, Lyell was equally impressed during his visit to Sweden in 1834, where he saw along the coast granite boulders that appeared to have been carried by floating ice[10]. He was also impressed by accounts from mariners of boulders carried on icebergs. Not long after his excursion with Agassiz, he was told of similar observations made by Joseph Hooker on the James Clark Ross expedition to Antarctica in 1839–41. Darwin too had reported rocks being carried out to sea by icebergs broken off from glaciers in southern

Chile, as Lyell reported in his *Elements of Geology*. Lyell just missed observing this phenomenon for himself when he was crossing the Atlantic on his way to and from the Americas in the mid to late 1840s[38]. Writing to his sister Carry from the steamship *Britannia* in June 1846, he reported, '*We passed fifty icebergs or more in daylight … One iceberg … which came close to us when I was below, had a large rock twelve feet square on the top and as much gravel and dark sand on its side*'[25]. While this confirms my own observation that such occurrences are rare, it was enough to make Lyell stick to icebergs as accounting for the distribution of erratic blocks away from mountainous glaciated regions like Scotland and Scandinavia, no matter what Agassiz said.

Like Agassiz, Lyell also saw glacial erratics in North America. During his visit to the United States in 1853, his host James Hall took him to see trains of erratic boulders in the Berkshire Hills of western Massachusetts. Lyell's biographer explains[39], '*The boulders were distributed in long parallel rows, extending in nearly straight lines across ridges and valleys from their starting points on the Canaan Ridge. Their direction was nearly at right angles to the lines of the ridges and bore no relation to the direction of the streams and rivers. The boulders were rounded like the glacial boulders called in Switzerland roches moutonnés … one of the larger boulders … [near the meeting house in Richmond] was fifty-two feet long, forty feet wide, and, although partially buried, fifteen feet high*[40]*. The boulders rested on a deposit resembling the European "northern drift". Where the underlying rock was exposed, its surface was polished, striated, and furrowed, with the furrows running in the same direction as the trains of boulders. Lyell thought that the trains of boulders must have been transported by floating ice at a time when the Berkshire hills stood at a much lower level, with only their highest ridges protruding above the sea. He thought their transport could not be explained by glaciation, because if glaciers had transported the boulders, the trains of boulders should have been distributed down the valleys instead of across them. In fact, the boulders had been transported by glaciers, but by continental glaciers rather than by mountain glaciers, the only ones with which Lyell was familiar.*' Nowadays, we would say 'transported by continental ice sheets' rather than by continental glaciers.

The contrast between Lyell and Agassiz was one of vision. Lyell stuck to what he knew to be true: glaciers occupied valleys and carried boulders down them, and, where they met the ocean, icebergs carrying boulders might break off and carry their burden of rocks out to sea. Agassiz could envision a merging of mountain glaciers into great sheets of ice covering entire landscapes, ploughing across and shaping the land and dumping clay and boulders en route. 'God's Great Plough', he called the ice sheet.

Although in later years he would back away from Lyell's adherence to transport by icebergs, Charles Darwin initially followed Lyell's line closely in a paper on the glaciers of Caernarvonshire, in Wales[41]. Investigating the moraines near Lakes Ogwyn and Idwell in the Welsh mountains, he deduced that the glaciers from the valleys in which those lakes now sat had formerly united and plunged down the valley of Nant-Francon towards Bethesda, where they had dumped in the sea a whitish earth full of rounded and angular boulders that were deeply scored like the rocks over which a glacier had passed. Following Lyell's line, he assumed that the boulders had been dropped into this mud from floating icebergs, and that the land had since been uplifted. '*By this means*', he said, '*we may suppose that the great angular blocks of Welch [sic] rocks scattered over the central counties of England were transported*'[41]. He concluded '*that the whole of this part of England was, at the period of the floating ice, deeply submerged … I do not doubt that at this same period the central parts of Scotland stood at least 1300 feet beneath the present level, and that its emergence has since been very slow. The mountains at this period must have formed islands, separated from each other by rivers of ice, and surrounded by the sea*'[41]. Lyell would have approved.

Like Lyell, Darwin accepted that there must also have been vast thicknesses of land ice locally, as a source for floating icebergs. His letter to W.H. Fitton[42] is a reminder that one may often not be able to 'see' what is under one's nose. On a field trip to Capel Curig in North Wales, he wrote: '*the valley about here, & the Inn, at which I am now writing, must once have been covered by at least 800 or 1000 ft in thickness of solid Ice! – Eleven years ago, I spent a whole day in the valley, where yesterday every thing but the Ice of the Glacier was palpably clear to me, and then I saw nothing but plain water, and bare Rock. These glaciers have been grand agencies*'[42]. But he then went on to extol the virtues of the power of drifting icebergs to distribute erratic blocks: '*I am the more pleased with what I have seen in N. Wales, as it convinces me that my views, on the distribution of the boulders on the S. American plains having been effected by floating Ice, are correct*'[42]. It would take a lot for Darwin to withdraw support from Lyell.

Lyell stuck to the iceberg theory more or less unchanged throughout his life. In the second edition of his *Elements of*

Geology, published in 1841, he admitted that small glaciers might once have existed in Scotland, but dismissed the theory that the widespread British deposits of 'glacial till', comprising mixed boulders and clay, had been deposited beneath an ice sheet, preferring still to think of them as deposited from floating icebergs. By the time he published *Antiquity of Man* in 1863, he had accepted the refrigeration of the climate in the post-Tertiary Pleistocene that Agassiz had postulated, and that this had led to large areas of Britain and northwestern Europe becoming covered by 'glacial drift'. Lyell's hypothesis that boulder clay was deposited from floating icebergs required that much of England north of a line joining the estuaries of the Thames in the east and the Severn in the west, as well as much of the northwest European plain, had been submerged. He explained away the grooves carved into exposed rocks on hillsides as having been made by stones embedded in the bottoms of icebergs, rather than – as Agassiz would have it – by stones embedded in a moving ice sheet.

Lyell accepted that the ice originated in glacial dispersion centres on highlands in Scandinavia, Scotland, Wales and the English Lake District. But he thought that those centres were limited in extent and discharged their ice into a surrounding ocean, rather than into a surrounding ice sheet like that of Greenland. Lyell also agreed with Agassiz's suggestion that within those distribution centres, glacial lakes dammed by ice were locally important, the beaches of different lake levels explaining the terraces or 'parallel roads' around Scotland's Glen Roy. His interpretation of the terraces around Glen Roy was not original: it had first been proposed by the Scottish geologist John MacCulloch in 1817, when he was president of the Geological Society of London.

Where Lyell and Agassiz differed profoundly was in explaining the origin of the glacial drift. In *Antiquity of Man*, Lyell expanded on his marine glacial theory, suggesting that during the Ice Age much of England and northwest Europe must have been submerged to depths of more than 600 feet, Scotland to depths of as much as 2000 feet and Wales to a depth of 1350 feet. By 1875, in the 12th edition of *Principles*, these figures had changed to 'perhaps' 500 feet in Scotland and 2000 feet in Wales. As is clear from that edition, much of his argument for submergence rested upon the occurrence of seashells at high altitudes among the boulder clay. For someone who denied any role for catastrophism in geology, Lyell was sailing close to the wind in invoking unexplained forces that could periodically lift the United Kingdom and Europe above the sea and then submerge them, during the small amount of geological time represented by the Ice Age.

By 1848, Darwin began to realise that sticking to the Lyellian view required some contorted thinking[43]. Trying to answer a common criticism of the time – that floating ice could not carry erratic blocks from a lower to a higher level – he suggested that, with repeated subsidence of the land, floating ice could gradually deposit boulders at progressively higher levels. Special pleading, indeed! The subsidence would have to have been significant and more or less immediate, something for which there was no apparent mechanism, and to have been continually repeated. A certain Mr Nicol objected '*that when the parent rock was once submerged, no further supply of boulders could be derived from it*'[43]. Darwin confessed, '*this appears to me an objection of some force*'[43]. Well he might! Not to be deterred, he argued that the piling up of ice by storms along a shore would raise boulders above their original level. Rather a weak response, considering that erratic boulders of immense size occurred 900–1000 feet above the strata from which they had been carved. He would recant, as we see in Chapter 3.

Enter Archibald Geikie (1835–1924) (Figure 2.9, Box 2.4), a young Scottish geologist, who roundly criticised Lyell's iceberg transport theory early in the 1860s.

From his detailed examination of the Ice Age geology of Scotland, Geikie concluded that the land must have been shaped by the actions of a giant ice sheet, the remains of which mantled its surface as 'drift' deposits[44]. Geikie called for the iceberg theory to be abandoned forthwith. He said that he hoped he might have convinced Lyell of

Figure 2.9 *Archibald Geikie.*

Box 2.4 Archibald Geikie.

Archibald Geikie was born in Edinburgh and educated at the university there. He became an assistant for the British Geological Survey in 1855, worked extensively on the geology of Scotland, was elected a fellow of the Royal Society in 1865 and was appointed director of the Geological Survey of Scotland when it was formed in 1867. While in that post he became the first Murchison Professor of Geology and Mineralogy at the University of Edinburgh in 1871, and he held those two posts together until 1881, when he was appointed director-general of the Geological Survey of the UK and director of the Museum of Practical Geology in London. Geikie was president of the Geological Society of London in 1891–92, was awarded the Murchison Medal by that Society in 1895, received the Royal Medal from the Royal Society in 1896 and became president of the Royal Society in 1909. He was knighted in 1891.

the correctness of his conclusions. Lyell did read Geikie's book, writing to his wife in May 1863 that '*Geikie's book on the Glacial Period in Scotland is well done …* '[25]. Nevertheless, that same year – 1863 – Lyell published *Antiquity of Man*, with its illustrations showing Great Britain drowned beneath an iceberg-flooded sea! In the 12th edition of his *Principles*, Lyell continued with his ice-flooded sea, but conceded a little ground to Geikie, noting that in Scotland '*some examples of this … striation may have been due to the friction of icebergs on the bed of the sea during a period of submergence; others to a second advance of land glaciers over moraines of older date*'[27].

Lyell did reverse his conclusion about seaborne transport in one case. In the 12th edition of *Principles*, he reported that, on a visit to Switzerland in 1857, the local geologists had convinced him that an ice sheet had filled the Valley of Switzerland between the Alps and the Jura and transported down into it and up the other side the erratic blocks now found 50 miles away from the Alps, atop the Jura Mountains. Writing to his father-in-law, Leonard Horner, from Zurich in 1857, he said, '*If the hypothesis now adopted here to account for the drift and erratics of Switzerland, the Jura, and the Alps be not all a dream, we must apply the same to Scotland, or to the parts of it that I know best. All that I said in May 1841 on the old glaciers of Forfarshire … I must reaffirm*'[25]. In a letter to J.W. Dawson in February 1858, he went further, calling for glaciers (not icebergs) to transport erratics and drift on to the plains of the River Po in northern Italy[25].

By the 12th edition of the *Principles*, Lyell's conversion to the Ice Age cause was more or less complete. He recalled seeing that many of the rocky surfaces exposed in Switzerland were '*smoothed and polished, and scored with parallel furrows, or with lines and scratches produced by hard minerals … The discovery of such markings at heights far above the surface of the existing glaciers, and for miles beyond their present terminations,*' he said, '*affords geological evidence of the former extension of the ice beyond its present limits in Switzerland and other countries*'[27]. Although this meant that Agassiz had been right all along about the Swiss erratics, Lyell could not accept that Agassiz's theory could be extended beyond the Swiss region, except in mountainous places like Scotland (and presumably Scandinavia).

Next into the lists was yet another Scottish geologist, James Geikie (1839–1915) (Figure 2.10, Box 2.5), younger brother of the more famous Sir Archibald.

Following in his illustrious brother's footsteps, James amassed a vast storehouse of knowledge of the geology of the glacial and interglacial periods of the Ice Age from all over the world, publishing his tome *The Great Ice Age* in 1874[45]. The comprehensive 3rd edition, published in 1894, included a chapter on the glaciations of North America by the great American geologist T.C. Chamberlin. James's most telling fact came from Nansen's observation that ground moraines beneath the Greenland ice sheet were visible in arches and tunnels under the ice front, where one

Figure 2.10 *James Geikie.*