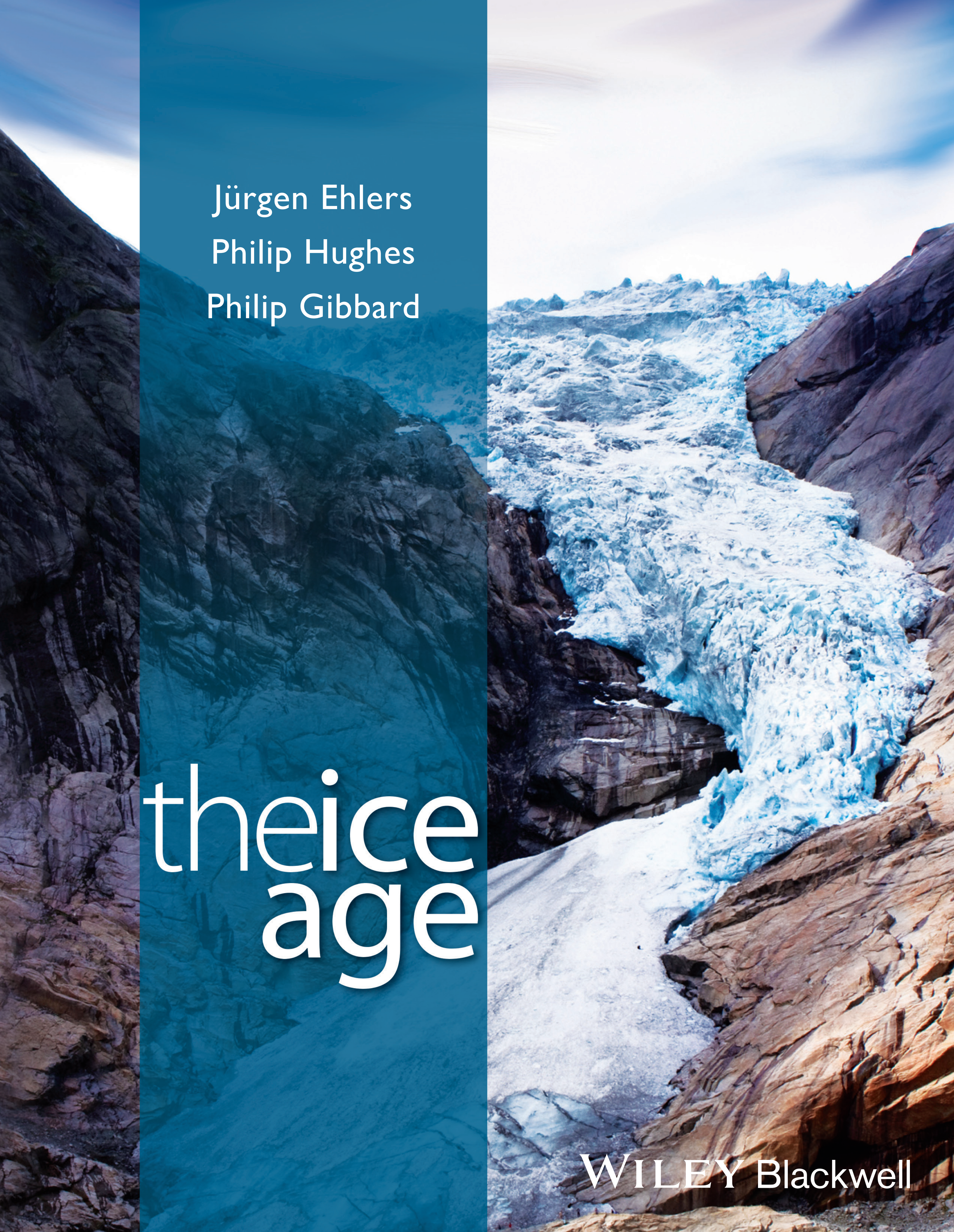

Jürgen Ehlers
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the ice age

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The Ice Age

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Jürgen Ehlers worked as a Quaternary geologist at the Hamburg State Geological Survey, where he was responsible for geological mapping of the city area, from 1978 until 2013. He has taken part in international research projects. Together with Phil Gibbard and Phil Hughes, he has coordinated the INQUA project 'Extent and Chronology of Quaternary Glaciations'. He is regarded as an expert in Quaternary geology. He is the author of several books on aspects of the Ice Age and about the history and development of the North Sea. He is also Associate Editor of the German Quaternary Association's (DEUQUA) journal *Eiszeitalter und Gegenwart*.

Phil Hughes is Reader in Physical Geography at The University of Manchester. He studied for his first degree in Geography at the University of Exeter, graduating in 1999. This was followed by a Masters in Quaternary Science and a PhD in Geography, both at the University of Cambridge (Darwin College). His PhD, entitled *Quaternary Glaciation in the Pindus Mountains, Northwest Greece*, was completed during 2001–2004 under the supervision of Phil Gibbard (Cambridge) and Jamie Woodward (then Leeds, now Manchester). Phil has since published widely on glaciations in the Mediterranean mountains and his research has included work in Morocco, Spain, Montenegro, Albania and Greece. He has also published on various aspects of glaciation in the British Isles, as well as several theoretical papers on stratigraphy and glacier–climate modelling. Phil collaborated with both Jürgen Ehlers and Phil Gibbard in the recent edited volume of global glaciations (*Quaternary Glaciations—Extent and Chronology: A Closer Look)*. Since 2011, Phil has also been Subject Editor for Quaternary Science and Geomorphology for the *Journal of the Geological Society of London*.

Phil Gibbard is Professor of Quaternary Palaeoenvironments in the Department of Geography, University of Cambridge and was a founder member of the Godwin Institute of Quaternary Research (since January 1995), now known as Cambridge Quaternary. He is concurrently a Docent (Adjunct Professor) in the Department of Geosciences and Geography, University of Helsinki where he contributes to the teaching of Quaternary Geology. Phil Gibbard studied Geology at the University of Sheffield in the 1960s, then took his PhD at the University of Cambridge under the supervision of Richard West FRS. He has published extensively on many aspects of Quaternary science. He has published numerous books with Jürgen Ehlers, including a translation of *Quaternary Geology and Glacial Geology* (John Wiley & Sons, 1996). In recognition of Phil's contribution to

Quaternary Science he has received numerous awards, including an honorary doctorate degree (PhD *honoris causa*) from the University of Helsinki (2010); a Doctor of Science (ScD) degree from the University of Cambridge (2010); the André Dumont Medal (2014) from Geologica Belgica; and the James Croll Medal 2014 from Britain's Quaternary Research Association. He was President of the International Commission on Stratigraphy's Subcommission on Quaternary Stratigraphy during 2002–2012. In 2011 he was elected President of the INQUA Commission on Stratigraphy and Geochronology (SACCOM) in 2011. He is also a member of the editorial boards of several journals.

Preface

The Ice Age is the period in which we live; our present interglacial interval is part of the Ice Age. The Ice Age has been a period of extreme climatic variations which are continuing today. Temporarily vast ice sheets covered major parts of the northern continents. At other times, the Sahara was green and inhabited by humans and Lake Chad, which today is the size of Greater London, once covered an area 20% larger than Britain and Ireland combined.

What happened in the Ice Age can only be reconstructed from the traces left behind. The Ice Age created strata that differ from the deposits of other geological periods. This book describes the processes which formed them and the methods by which they can be investigated. In this sense, an Earth scientist's work resembles (and is as exciting as) that of a detective.

This book builds on the original German language edition, *Das Eiszeitalter* (2011; Spektrum Akademischer Verlag) by Jürgen Ehlers. This was also the title of Paul Woldstedt's classic German language textbook on Quaternary geology, which was published in several editions by Ferdinand Enke Verlag. To emphasize the connection between the dramatic climate changes of the past and our present world (Woldstedt 1950), Paul Woldstedt named the journal of the German Quaternary Association (DEUQUA) *Eiszeitalter und Gegenwart* (Ice Age and Present). Jürgen Ehlers did not experience this early phase of German Quaternary research; Paul Woldstedt died in 1973, the year before Ehlers first participated in a DEUQUA meeting at Hofheim.

Since the publication of Woldstedt's *Eiszeitalter*, much has changed. The Ice Age is the period during which humans began to interfere with nature. The changes brought about by such interference are evident around us, and all relevant data are freely available. The idea of what a textbook should look like in order to appeal to the reader has also changed. This book does not merely aim to add another to the market; it is intended to offer a personal vision on the Quaternary, building on the very different experiences and perspectives of the three authors.

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Many colleagues and friends have critically checked parts of the book and/or contributed illustrations. They include: Dr Hinrich Bäsemann, Tromsø; Dr Jochen Brandt, Helms-Museum, Harburg; Professor Dr Detlef Busche, Universität Würzburg; Dr Gerhard Doppler, Bayerisches Geologisches Landesamt; Professor Dr Edward Evenson, Lehigh University, Pennsylvania; Professor Dr Peter Felix-Henningsen, Universität Gießen; Professor Dr Markus Fiebig, Universität für Bodenkultur, Wien; Professor Dr Magnús Tumi Guðmundsson, University of Iceland, Reykjavik; Dr Bernd Habermann, Stadtarchäologie Buxtehude; Dr Robert Hebenstreit, Freie Universität Berlin; Professor Dr Dieter Jäkel, Freie Universität Berlin; Dr Adriaan Janszen, London; Professor Dr Kurt Kjær, Natural History Museum, Kopenhagen; Professor Dr Keenan Lee, Colorado School of Mines; Dr Christian Hoselmann, Hessisches Landesamt für Geologie und Umwelt; Professor Wighart von Koenigswald, Universität Bonn; Marcus Linke, Landesbetrieb Geoinformation und Vermessung, Hamburg; Professor Dr Thomas Litt, Universität Bonn; Professor Dr Juha-Pekka Lunkka, University of Oulu; Steve Mathers, British Geological Survey, Nottingham; Professor Dr Andrea Moscariello, University of Geneva; Professor Dr Jan Piotrowski, University of Aarhus; Professor Dr Frank Preusser, Universität Freiburg; Professor Vladimir E. Romanovsky, University of Alaska, Fairbanks; Professor Dr Alexei Rudoy, Tomsk State University; Professor Dr Gerhard Schellmann, Universität Bamberg; Professor Dr Christian Schlüchter, Universität Bern; Dr Petra Schmidt, Witzeeze; Gertrud Seehase, Ratzeburg; Professor Dr John Shaw, University of Alberta, Edmonton; Eva-Maria Stellmacher-Ludwig, Wentorf; Dr Hans-Jürgen Stephan, Kiel; Dr Þröstur Þorsteinsson, University of Iceland, Reykjavik; Professor Dr Roland Vinx, Universität Hamburg; Dr Stefan Wansa, Landesamt für Geologie und Bergbau Sachsen-Anhalt; Gerda and Holger Wolmeyer, Hamburg; Professor Dr Jan Zalasiewicz, University of Leicester; Jacob G. Zandstra, Heemskerk; and Professor Dr Bernd Zolitschka, Universität Bremen. It is a pleasure to thank them all. We would also like to thank Elaine Rowan for her thorough copy-editing of this English edition.

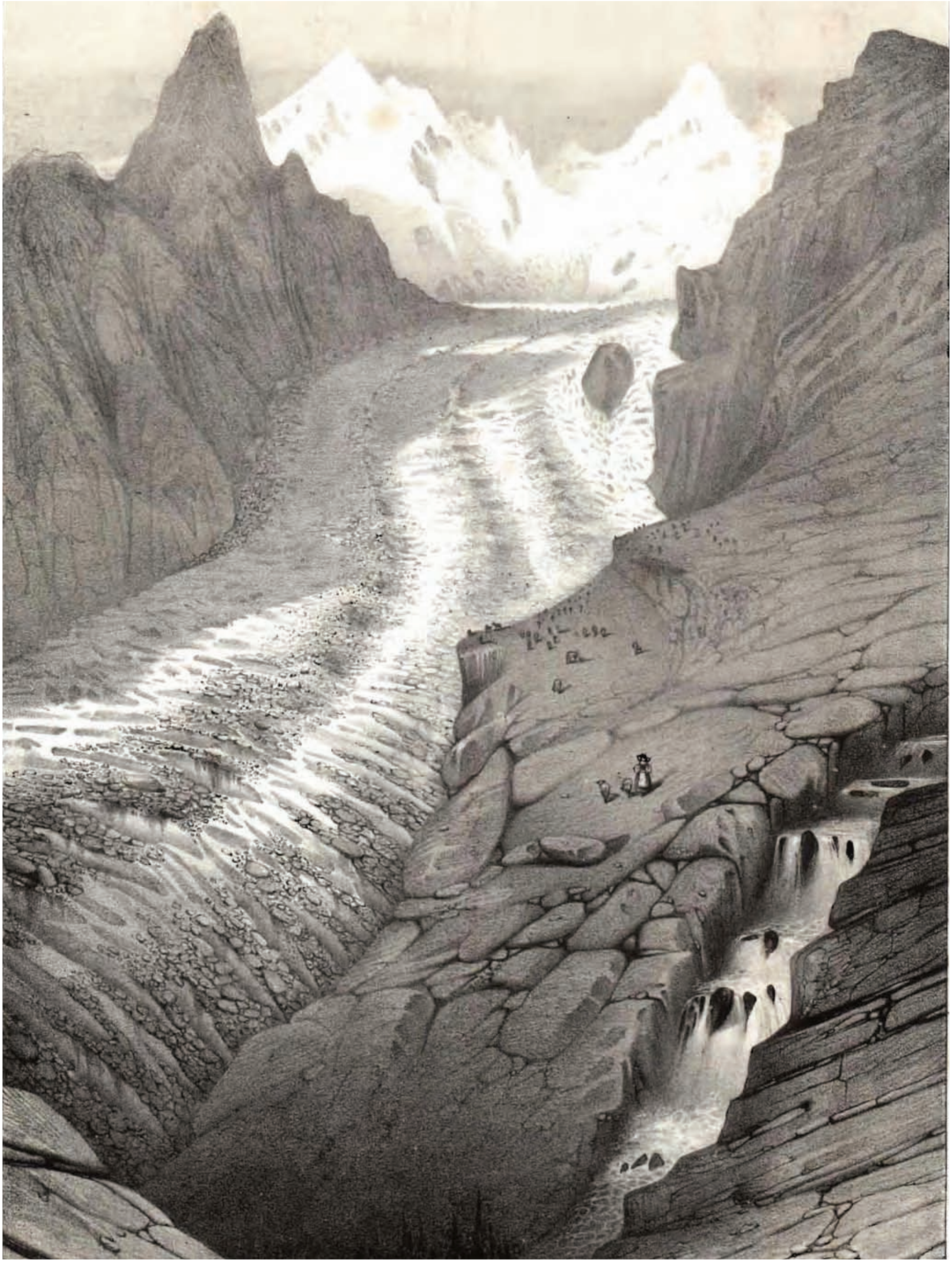
About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/ehlers/iceage

The website includes:

- Powerpoints of all figures from the book for downloading
- Pdfs of all tables from the book for downloading



Central part of Gorner Glacier, Switzerland. Source: Agassiz (1841).

Chapter 1
Introduction

> *The Ice Ages! It is difficult, now, to understand the perplexity and bafflement and sheer disbelief that greeted this idea, over a century and a half ago: the idea of vast walls of ice invading from the north to engulf entire landscapes. This seemed like science fiction, a Gothic fantasy on a par with a belief in dragons and fairies and industrious aliens that built canals on Mars.*
>
> Zalasiewicz (2009, p. 68)

The meeting of the Swiss Society of Natural Science on 24 July 1837 in Neuchâtel began with a scandal. The young president of the Association, Louis Agassiz, spoke not about the latest results of his studies on fossil fishes as expected, which had made him famous. Instead, he decided to talk about the erratic blocks in the Jura Mountains (and in the vicinity of Neuchâtel) which he said were the legacy of a major glaciation. This 'Discourse of Neuchâtel' is considered the birth of the Ice Age Theory.

Agassiz was not the first person to have said this, but he was the first high-ranking scientist. His speech met with icy disapproval. On the subsequent field trip on 26 July, during which the participants could actually examine the evidence with their own eyes, Agassiz did not succeed in convincing the other experts. The glacial theory appeared to be a non-starter (Imbrie & Imbrie 1979).

The Ice Age, First Edition. Jürgen Ehlers, Philip D. Hughes and Philip L. Gibbard.

Companion website: www.wiley.com/go/ehlers/iceage

1.1 In the Beginning was the Great Flood

People always tend to explain incomprehensible natural phenomena by processes they know. The notion of an 'Ice Age' was alien to the scientists of earlier centuries. They did know however that, in the course of the Earth's history, back and again extensive areas of land had been inundated by the sea. It therefore seemed to make sense to interpret the legacy of the Quaternary, especially the erratic blocks, as the results of a great flood. Did not the Bible report a devastating deluge? In many parts of the Earth there were traces of that flood to be found. Johann Friedrich Wilhelm Jerusalem listed some of them. He wrote:

> *The greatest attention deserve the southward pointed shape of Africa and India, and all the great embayments all around Asia, from the Red Sea up to Kamchatka, all open to the south, which are the surest proof that the Earth once suffered a violent flood from the south, which is also confirmed by the large amount of skeletons of large land animals found in Siberia which are derived from a more southern country.*
>
> Jerusalem (1774)

When Jerusalem published these lines, belief in the literal meaning of biblical texts had ceased. Jerusalem, adviser to Duke Karl I of Brunswick-Wolfenbüttel, was one of the most important theologians of the German Enlightenment. He was an educated man who had spent years in Holland and England. In his interpretation of the flood, he includes the dead mammoths from Siberia. He was well aware that 'petrified sea animals spread over the whole earth, such as the horns of Ammon' could not be related to the biblical flood, but a flood – a very, very big flood – still seemed possible.

That the latter might have been the biblical deluge was only believed by a few at the beginning of the 19th century. One of them, the Reverend William Buckland of Oxford, introduced the term 'Diluvium' to the stratigraphic nomenclature in 1823.

While his contemporary Cuvier was convinced that the traces of the deluge were limited to the lowlands and valleys of the Earth, Buckland wrote:

> *The blocks of granite, which have been transported from the heights of Mont Blanc to the Jura mountains, could not have been moved from their parent mountain, which is the highest in Europe, had not that mountain been below the level of the water by which they were so transported.*
>
> Buckland (1823, p. 221)

Cuvier also wrote:

> *In certain countries, we find a number of large blocks of primitive substances scattered over the surface of secondary formations, and separated by deep valleys or even by arms of the sea, from the peaks or ridges from which they must have been derived. We must necessarily conclude, therefore, either that these blocks have been ejected by eruptions, or that the valleys (which must have stopped their course) did not exist at the time of their being transported; or, lastly, that the motions of the waters by which they were transported, exceeded in violence anything we can imagine at the present day.*
>
> Cuvier (1827, p. 23)

This early attempt at a natural explanation for the occurrence of boulders far from their source rocks corresponds to the rolling stone or mud flood theory, mainly advocated by Leopold von Buch (1815), but also by Alexander von Humboldt (1845) and the Swedish physician and scientist Nils Gabriel Sefström (1836). They assumed that the erratics had been transported by huge masses of water, the so-called 'petridelaunic flood'. The reason why such masses of water would have been released and flooded out of the Alps and the mountains of Scandinavia remained open.

In England, Charles Lyell had argued in his *Principles of Geology* (1830–33) against the geological significance of disasters. Von Hoff was the first German scientist to turn against Cuvier's catastrophism (1834). Neptunists quarrelled with Plutonists, and eventually the concept of a smooth transformation of the Earth seemed to prevail.

A new interpretation of the erratic blocks was found at the beginning of the 19th century. In a shallow, cold sea icebergs might have transported the boulders. The supporters of the drift theory (Box 1.1), including Darwin and the physicist Helmholtz, were not completely opposed to a larger extension of the former glaciers, but rejected large-scale glaciation. Even when Lyell (1840) discussed the origin of erratic boulders in northern Europe, he was strongly opposed to the neo-catastrophism envisaged by Agassiz.

BOX 1.1 DRIFT-ICE TRANSPORT

The sandstone block in Figure 1.1 is 185 × 175 × 135 cm in size and its weight is estimated at 8 tons. It was found on a salt marsh covered with *Spartina alterniflora*. When the stone was pushed landward by drift ice, it left behind a distinct furrow in the ground (foreground right).

Figure 1.1 A block of sandstone on the lower saltmarsh at Isle-Verte, St Lawrence Estuary, Canada. Photograph by Jean-Claude Dionne.

(continued)

BOX 1.1 DRIFT-ICE TRANSPORT *(CONTINUED)*

Goethe had also heard that drift ice should have transported rock material from Sweden across the Øresund to Denmark. Was this the method by which the boulders in northern Germany had arrived in their present position?

There is no doubt that drift ice can move large stones. The coastal waters of northern Canada are covered with ice in winter. In the spring the ice cover breaks up, resulting in an ice drift along the coast. In its course, frozen rock and soil material are moved and redeposited. The Canadian geographer Jean-Claude Dionne has studied this phenomenon in numerous publications.

Figure 1.2 shows a melting ice block which eroded a 25–30 cm thick layer of salt marsh and redeposited it further downshore. Icebergs produce significantly deeper scours. Corresponding plough marks from icebergs of the Weichselian glaciation are found on the seafloor, for instance in the North Sea.

Figure 1.2 Stranded ice floe with a thick layer of frozen-on soil in the St Lawrence Estuary, Canada. Photograph by Jean-Claude Dionne.

However, Agassiz did not capitulate. In 1840 he published his *Études sur les Glaciers,* followed a year later by the German edition *Studien über die Gletscher*. Both books were printed at the author's expense, and met a cool reception. Alexander von Humboldt advised Agassiz to return to his fossil fishes. 'In so doing,' he wrote, 'you will render a greater service to positive geology, then by 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' (quoted in Imbrie & Imbrie 1986).

Nevertheless, Agassiz eventually had success with his book. He provided evidence that the legacy of the glaciers could be traced from the current ice margin over a series of end moraines to the foothills of the Alps, and that the path of the erratic blocks could be followed from their source areas to the outer edge of the former glaciers. He had no hesitation in making his ideas public, not only in word but also in pictures. The lavishly illustrated 'atlas' conveyed the views of the author more persuasively than his words.

The scientific breakthrough came with his trip to Britain, where he finally managed to convince William Buckland of his theory. This in turn persuaded Charles Lyell, the most important geologist of his time, and in November 1840 together they presented their new insights to the professional world in front of the Geological Society of London. There was still much scepticism, but now the triumph of the Ice Age Theory was unstoppable.

Agassiz demanded a considerable imagination of his readers. He wrote:

> *At the end of the geological epoch that preceded the elevation of the Alps, the earth was covered with an immense crust of ice, which stretched forth from the polar regions over most of the northern hemisphere. The Scandinavian and British Peninsula (sic), the North Sea and Baltic Sea, northern Germany, Switzerland, the Mediterranean Sea to the Atlas, North America and Asian Russia, were just a single vast ice field, from which only the highest peaks of the then existing mountains … emerged.*
>
> Agassiz (1841, p. 284, translated from the German edition)

The discussion also aroused a great deal of interest from the public. Switzerland and its peaks were among the favourite destinations at the beginning of tourism (Figs 1.3–1.5). The first tourists were mostly English climbers who ventured into the Alps. The journey was initially difficult until, in the last decades of the 19th century, the railway made access much easier (Hachtmann 2007). The improved infrastructure in the Alps also made it easier for scientists to investigate the evidence of former glaciations in the field.

In northern Germany, the 'Glazialtheorie' still predominated. Charpentier (1842) had already postulated the existence of a former northwest European ice sheet that reached as far as England, the Netherlands, the Hartz Mountains, Saxony, Poland and 'almost to Moscow'. He fared no better than Bernhardi (1832) before him or Morlot (1844, 1847) after him. Bernhard Cotta (1848) wrote:

> *It surpasses the boundaries of the thinkable, to accept glaciers, which should have reached from the mountains of Norway to the Elbe River and as far as Moscow, and even to the coasts of England, and moved across this level ground, with its rough surface, laden with moraine … However, we know from observations in both polar regions of the Earth another kind of natural stone transport, which takes place continually, and which should be well suited to explain the northern boulders of Europe and America, as well as the erratic blocks in Patagonia. That is the transport by floating ice.*

The drift theory remained firmly in place in northern Germany for a few more decades (e.g. Cotta 1867; Box 1.2).

Figure 1.3 View from Gornergrat to Monte Rosa, Switzerland. Above: as seen by Agassiz (source: Agassiz 1841), below: 1979 (photograph by Jürgen Ehlers). The perspective is slightly different, but the decline of the ice on the opposite slope is clearly visible.

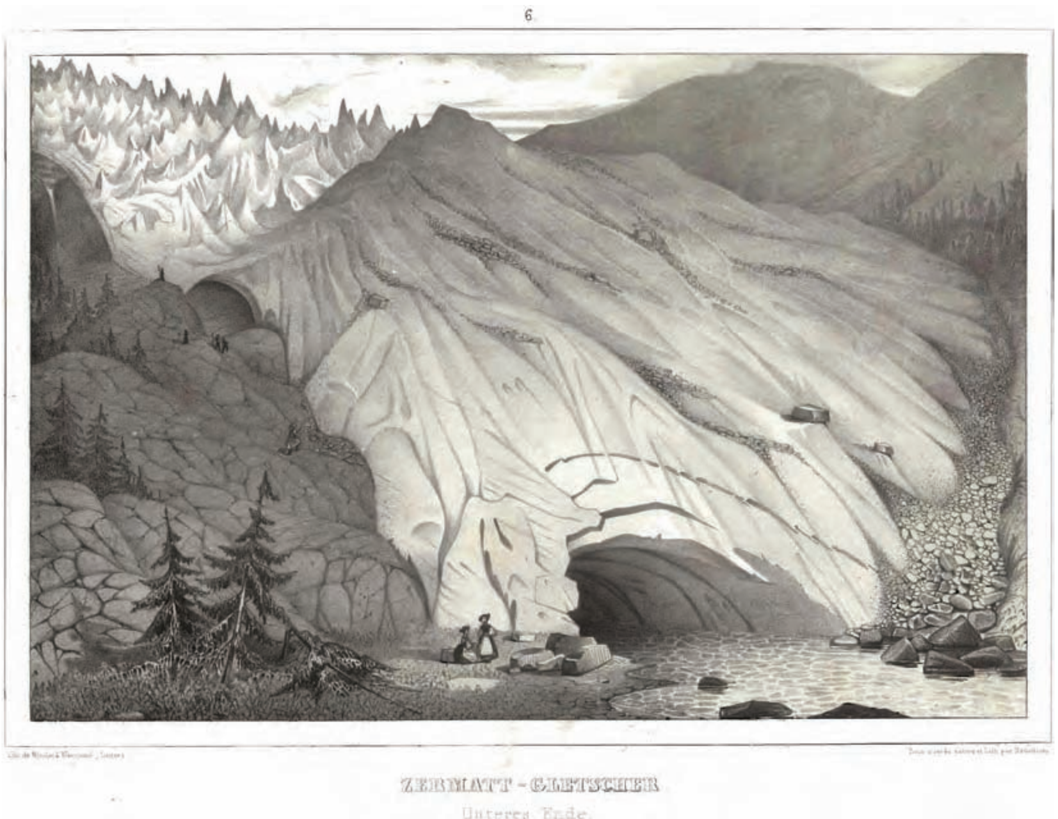


Figure 1.4 The lower end of the Gorner glacier (formerly called the Zermatt glacier). Neither of the two ladies at the foot of the glacier or the gentlemen on the adjacent rocks (left) seem to have work to do here; they are probably tourists. Source: Agassiz (1841).

Figure 1.5 An excursion onto the Glacier de Courbassière, Valais, Switzerland. The nineteenth century saw a strong growth in tourism in Switzerland. The wild nature and the glaciers were not only major tourist attractions, but had also become more accessible for scientific research. From the point where the postcard was taken, the glacier seems almost unchanged today. In truth, its length has shrunk by 800 m since 1889.

BOX 1.2 FINAL PROOF OF THE DRIFT THEORY?

Towards the end of the 1870s, Heinrich Otto Lang decided to address the issue of the North German 'Glazialtheorie' by investigating the local boulder inventory (Lang 1879). Lang was born on 10 September 1846 in Gera-Unterhaus; he received his doctorate in 1874 and then became a professor of mineralogy and geology at the University of Göttingen.

When it was brought to his attention that large gravel deposits had been found in Wellen, near Bremen, he had Professor Buchenau from Bremen and a Mr von der Hellen send him 180 stones. He asked them to collect not only those rocks that looked most interesting, but also those who presented 'the essential constituents of the deposit'.

Having received these stones, Lang faced a seemingly impossible task. His work was complicated by the fact that he had never been to Scandinavia, and that part of the relevant literature was not accessible to him. However, he was able to inspect samples from various geological collections including the petrographic collections of the Royal University of Göttingen, which held erratic boulders from the Coburgs (Hannover), Loitz (Pomerania), Denmark, Sweden and Iceland. The Icelandic rocks would have been of little use to him, just like the rocks that the first German North Pole expedition had collected.

Because of the high printing costs, the thesis could not be illustrated in colour. Lang had to resort to accurate description and did his best:

> *A brownish-red granite (Sample 156), the primary constituents of which are almost entirely made up of feldspar and quartz; to some extent the feldspars constitute a red matrix, in which, when seen with the naked eye, gray quartz grains are embedded, which, when polished, even appear black; other dark, less shiny, irregularly defined spots on the polished surface are sparse; in a crack that in one place includes the mouth of a cavity, traces of ferric hydroxide are found in places, or also a pale greenish mica-like mineral, and it is especially this fact, with makes the rock resembling a granite boulder from Zeitz in Thuringia (from Liebe's private collection) …*

Lang wondered: 'Could those stones have been brought by glacier to the north of Germany?' His answer was 'no'. As everybody knows, a glacier can only transport the rocks that it erodes in its source area. In this collection from Wellen, however, a wide variety of rock types was present which obviously did not all come from the same area. When considering transport by drifting icebergs, however, such mixing became far more likely.

Lang put great effort into his study and, even when his work was already in print, wrote some last-minute additions. To his surprise, he got the opportunity for a trip to Christiania (Oslo) and southern Scandinavia. Everything Lang found there confirmed his views: there had been no Ice Age. He concluded his study jokingly: 'One cannot save Mr. Torell the allegation that he has been playing with ice'.

All efforts were in vain, however. That same year Albrecht Penck's essay on the 'Boulder formation of North Germany' (1879) appeared, putting an end to any doubts concerning the 'Glazialtheorie' in the north of the German Empire.

On a field trip in conjunction with a meeting of the German Geological Society in Berlin (on 3 November 1875), the Swedish geologist Otto Torell (1875) noted the scratches on the Muschelkalk of Rüdersdorf, which Sefström (1838) before him had clearly identified as glacial striations. This observation signalled that a change of doctrine was long overdue. The glacial theory at that time had already been generally accepted for more than ten years in England and North America (Dana 1863; Lyell 1863) and Torell had also published his views on the Ice Age in northern Europe before (in 1865). At first, very few colleagues believed him.

The following year (1880) Felix Wahnschaffe found glacial striae at several points on the northern edge of the German uplands. He wrote: ‘In Velpke, some 5 km southwest of Oebisfelde, the surface of NE – SW trending almost horizontal sandstones which are overlain by boulder clay or glacial sand revealed in several quarries extraordinary glacial striae.’ The glacial striae belonged to two different ice advances. The older set, striking at 27°, is crossed by a younger system trending at about 84°. A large flagstone of Rhät sandstone was recovered and included in the collection of Royal Prussian Geological Survey. It can be seen in the collections of the Federal Institute for Geosciences and Natural Resources in Spandau, Berlin (Fig. 1.6).

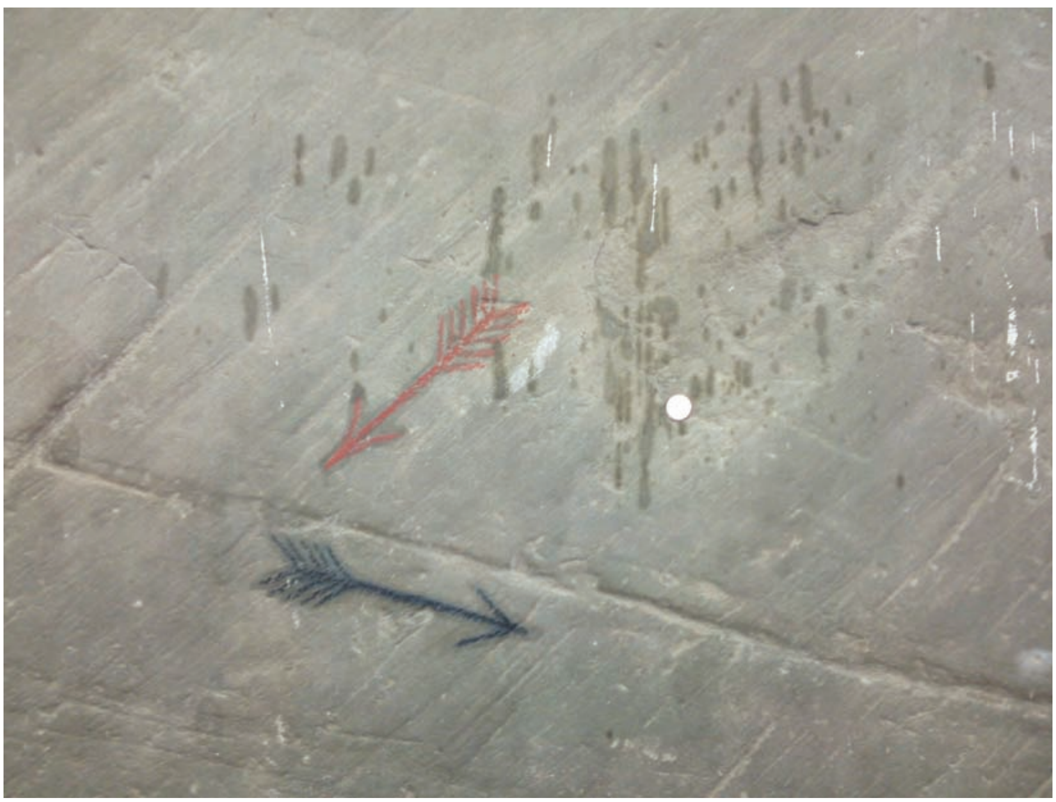
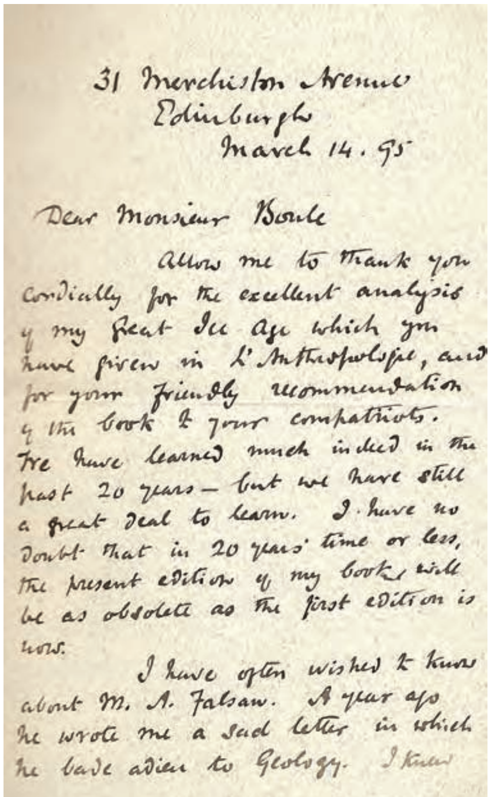


Figure 1.6 Slab of Rhät sandstone from Velpke (10 km ESE of Wolfsburg, Germany) with striae pointing in two different directions. The slab is located in the Museum of the BGR in Spandau. Photograph by Klaus Steuerwald.

Figure 1.7 Geikie's map showing the extent of the glaciers of the 'Third Glacial Epoch' (i.e. Weichselian) in Europe. The southern boundary of the glaciated area is nearly identical with the present state of knowledge. Source: Geikie (1894).

In Britain, James Geikie was a leading proponent of glacialism. In the 1894 edition of his book (first published 1874), Geikie had already included maps that showed the extent of three major glaciations in northern Europe (Fig. 1.7); the framework for more detailed mapping of the following decades was set. Geikie was in contact with the leading geologists of his time, and books and reprints were exchanged. Of course, one had to maintain friendly relations with foreign colleagues. Geikie wrote: 'Dear Monsieur Boule, Allow me to thank you cordially for the excellent analysis of my "Great Ice Age" which you have given in [the magazine] "L'Anthropologie", and for your friendly recommendation of the book to your compatriots …' Of course, it could not do any harm to send the good man a copy of the fully revised third edition as well (Figs 1.8, 1.9).

At that time, the origin of humankind was also of great general interest. Charles Darwin's *On the Origin of Species by Means of Natural Selection, or The Preservation of Favoured Races*



31 Merchiston Avenue
Edinburgh
March 14. 95

Dear Monsieur Boule

Allow me to thank you cordially for the excellent analysis of my Great Ice Age which you have given in L'Anthropologie, and for your friendly recommendation of the book to your compatriots. We have learned much indeed in the past 20 years – but we have still a great deal to learn. I have no doubt that in 20 years' time or less, the present edition of my book will be as obsolete as the first edition is now.

I have often wished to know about M. A. Falsan. A year ago he wrote me a sad letter in which he bade adieu to Geology. I knew

Figure 1.8 Letter in which Geikie thanks Professor Boule. Albert Faslan, mentioned in the letter, was a French natural scientist who had mapped the erratics in the Rhône catchment area. Source: Faslan & Chantre (1877/78).

Figure 1.9 The Wonders of the Primeval World, by Dr W.E.A. Zimmermann. Source: Zimmermann (1885).

in the Struggle for Life, published in 1859, triggered a lively debate among scientists and the public. Parts of his ideas were accepted very quickly (evolution); others, including the selection of species, only decades later. What did man look like in the past? Geikie described the findings, but he drew no picture. Others were less reticent (Fig. 1.10). Dr W.E.A. Zimmermann, for example, presented to his readers 'The miracles of the primeval world' (subtitled 'A popular account of the history of creation and original state of our world as well as the various periods of development of its surface, its vegetation and its inhabitants until the present time'). There were no questions unanswered. Images revealed, for example, 'The Lisbon Earthquake' (smoke, fire, sinking ships) or the 'Erebus volcano in the Southern Ocean' (before the smoking volcano, ice, high waves, sinking ships). A later 'Thirtieth Edition. Supplemented according to the latest state of scientific research' included erratic blocks, but in this 1885 edition these erratics were still accounted for by drift-ice transport.

An excellent illustrated overview of the history of the study of the ice ages is provided in Jamie Woodward's recent publication *The Ice Age: A Very Short Introduction* (2014).

Figure 1.10
Antediluvian man. The author makes fun of the artist who dares to publish 'an image of our antediluvian ancestors', but reprints it all the same. Source: Zimmermann (1885).

1.2 The Ice Ages of the Earth

It was known internationally by the middle of the nineteenth century that the Ice-Age glaciation was not an isolated case in Earth's history (Fig. 1.11). When geologists in northern Germany still believed in drift ice, traces of an older, Permo-Carboniferous ice age had been identified in the Indian subcontinent in 1856, in Australia in 1859 and in South Africa in 1868. Later in 1871 scientists were able to detect an even older great ice age of the Earth, which had taken place during the late Precambrian, the so-called Vendian (some 600 million years ago). Today an additional period at the end of the Ordovician has been added (Hirnantian), the ice sheets of which are probably limited to the Sahara. The first comprehensive overview of the Saharan glaciation was offered by Deynoux (1980). Moreover, the presence of other even older glacial periods in the Precambrian, about 950 and 2800–2000 Ma has been proven (Hambrey & Harland 1981; Harland et al. 1990).

The major glaciations still appear to be exceptions within the Earth's history. The spatial distribution of glacial sediments from these geological eras is by now fairly well known.

The exact location of the poles and the correlation of the scattered occurrences, however, often cannot be established with certainty. One of the few things that is certain is that the ancient glaciations, like their Pleistocene counterparts, had multiple phases.

In the tillite series of Scotland, which date from the latest Precambrian (Port Askeig Formation), numerous layers of rock are found that represent morainic deposits that have been turned into stone (tillite). Glacial deposits from this period have been found in many places all over the globe (e.g. Norway; Figs 1.12, 1.13), leading to the assumption that the Earth at that time might have experienced a long period during which its surface was completely covered by kilometre-thick ice sheets, making all life impossible. The press in particular have embraced this sensational idea. However, today it is known that there never was such a 'Snowball Earth'. Widespread black shales were found in the São Francisco craton in southeastern Brazil, formed during the Neoproterozoic glaciation about 740–700 Ma. The rock contains up to 3 weight percent (wt%) organic carbon, which could only be deposited under the condition that the sea was free of ice (Olcott et al. 2005). Moreover, when the composition of the Port Askaig deposits on Islay (Scotland; Fig. 1.14) is examined, it is found that at least part of the sequence was deposited in open water. Consequently, the glaciers of the Precambrian Varanger ice age were – just like their successors in the later ice ages – limited in extent (Harland 2007).

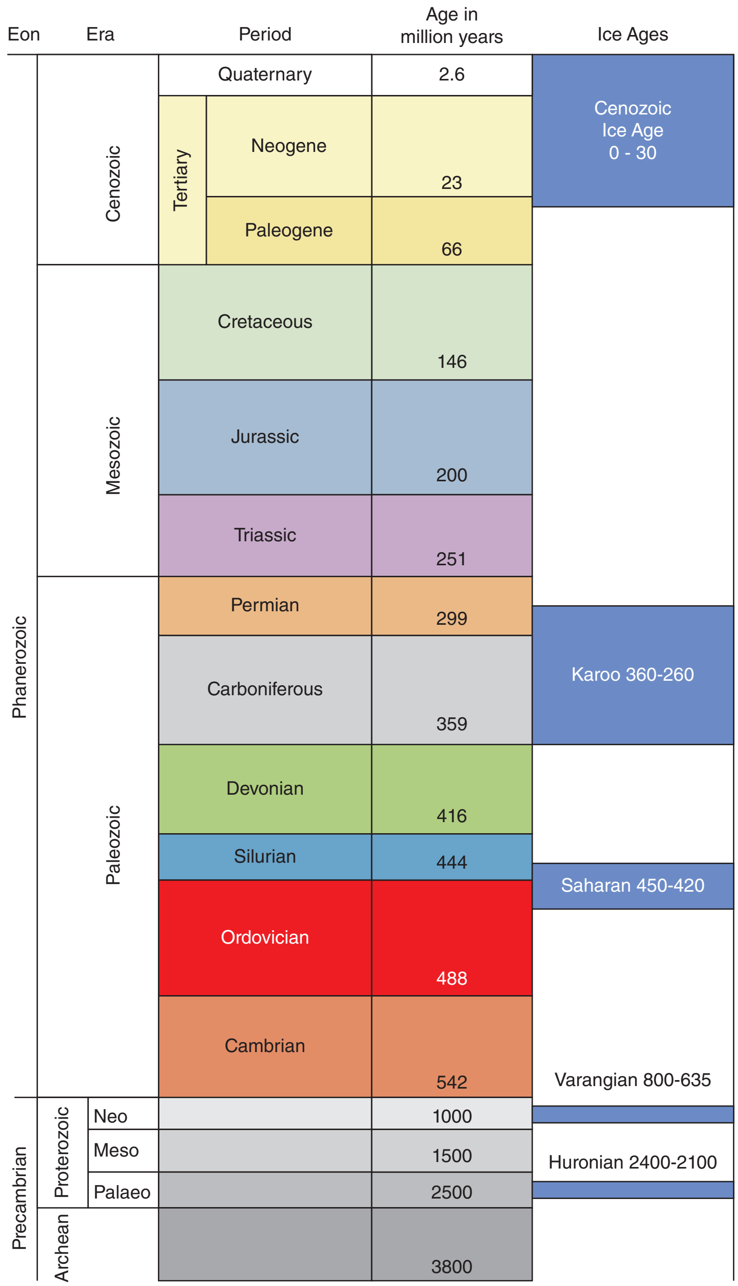


Figure 1.11 Geological timescale and the occurrence of ice ages in the Earth's history.

Traces of the Carboniferous glaciation are widespread in the southern continents (the former Gondwanaland), and are particularly well exposed in South Africa. Numerous recent studies have shown that those early glaciations left behind the full inventory of landforms and sediments that we know from the Quaternary glaciations.

Evidence of glaciation at the end of the Ordovician so far has been demonstrated from South Africa and the Sahara. From Europe, glacial deposits from only the latest Precambrian (Neoproterozoic) are known (from Scotland and Norway); corresponding layers are also found in Greenland, Asia, Africa and Australia. The oldest traces of glaciation occur in North America (Canadian Shield and Montana), South America (Brazil) and South Africa. However, those old deposits will not be discussed here. The presentation in this book is limited to the most recent Ice Age of the Earth's history: the Quaternary (see Box 1.3 for more information).

Figure 1.12 Neoproterozoic Moelv Tillite at Moelv, Lake Mjøsa, Norway. Above: overview; below: detail. Photographs by Jürgen Ehlers.