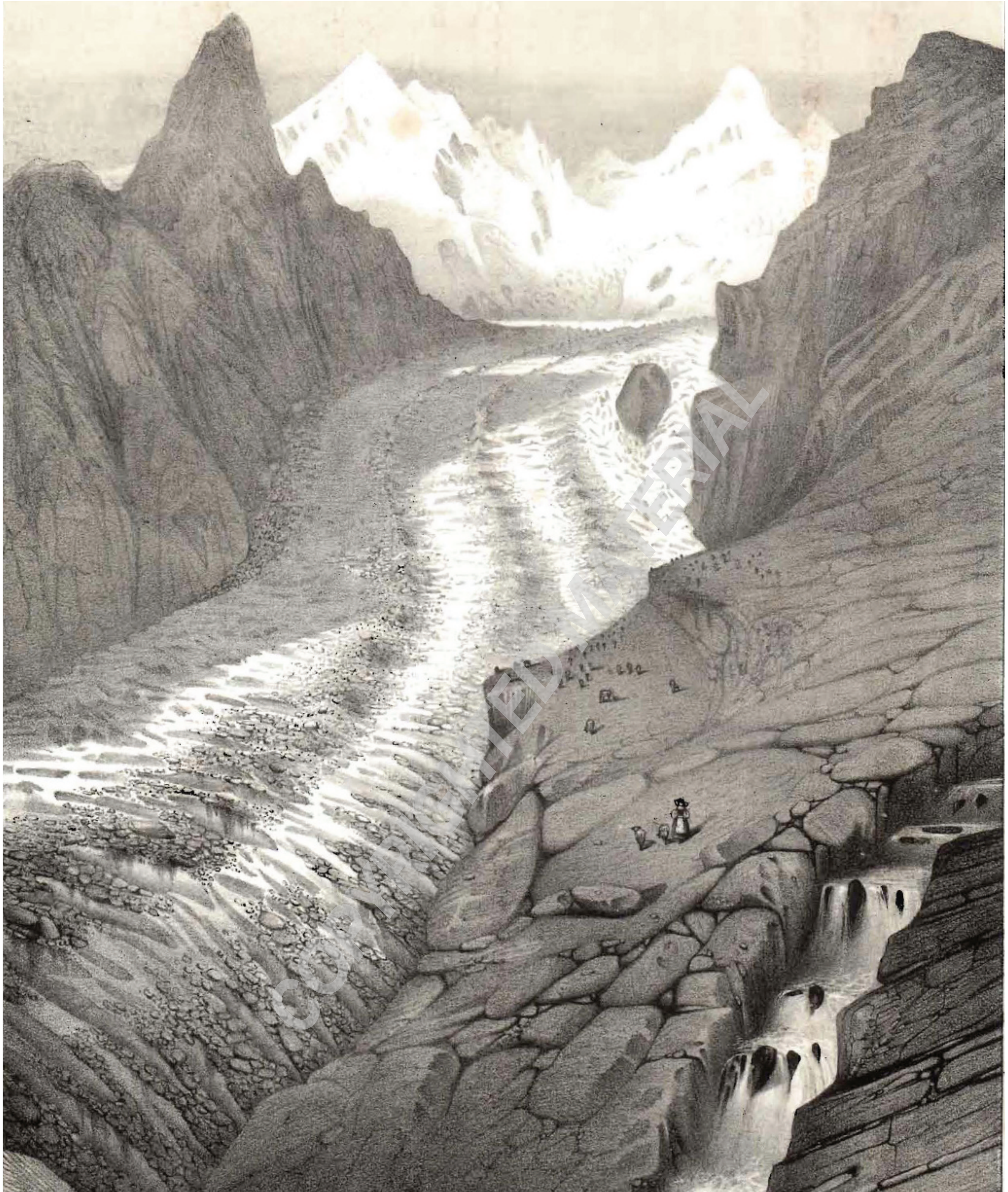


Central part of Gorner Glacier, Switzerland. Source: Agassiz (1841).

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).

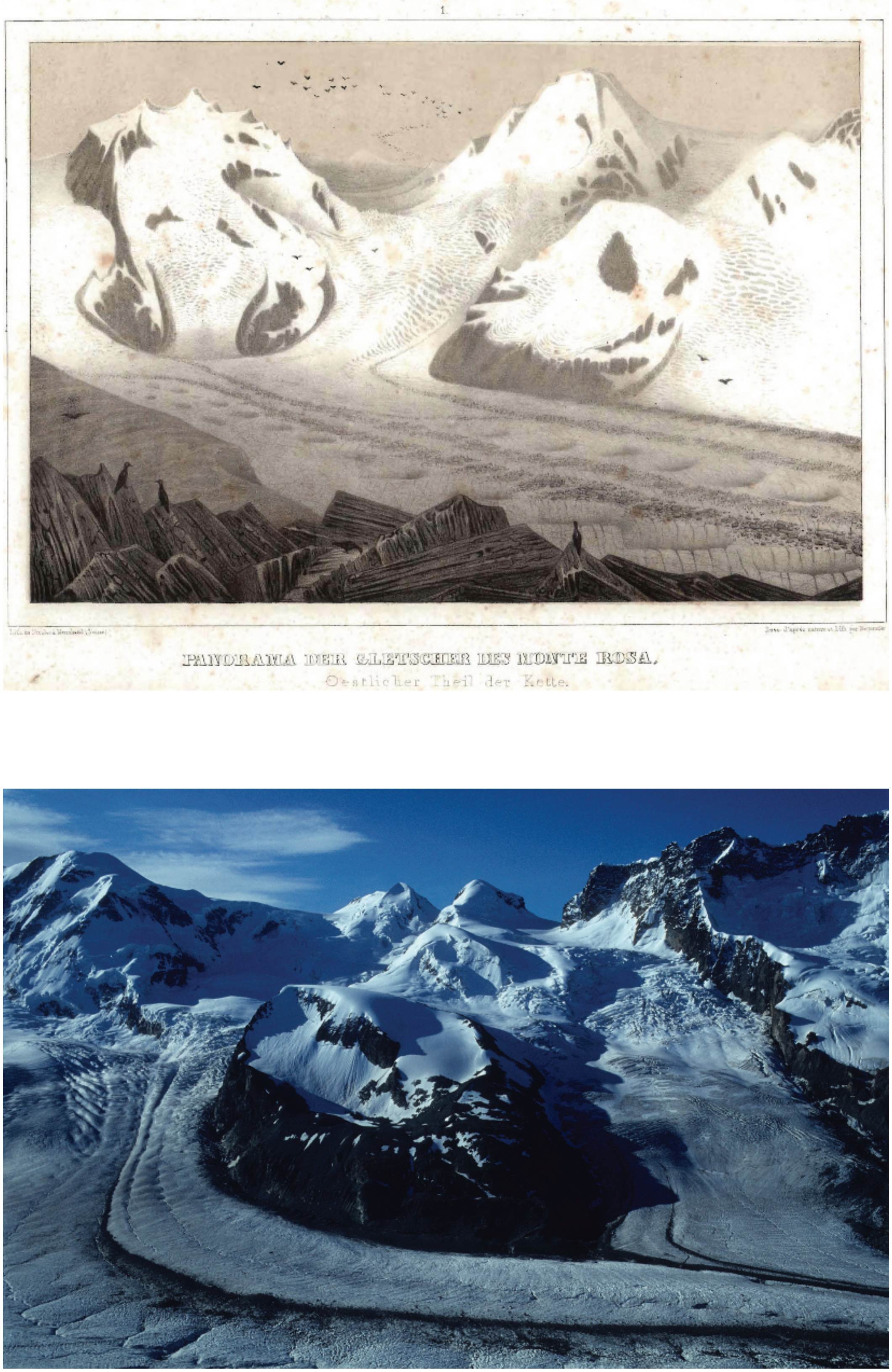


Figure 1.3 View from Gornergrat to Monte Rosa, Switzerland. Above: as seen by Agassiz (source: Agassiz 1841), below: 1979 (photograph by Jürgen Ehlers). The perspective is slightly different, but the decline of the ice on the opposite slope is clearly visible.

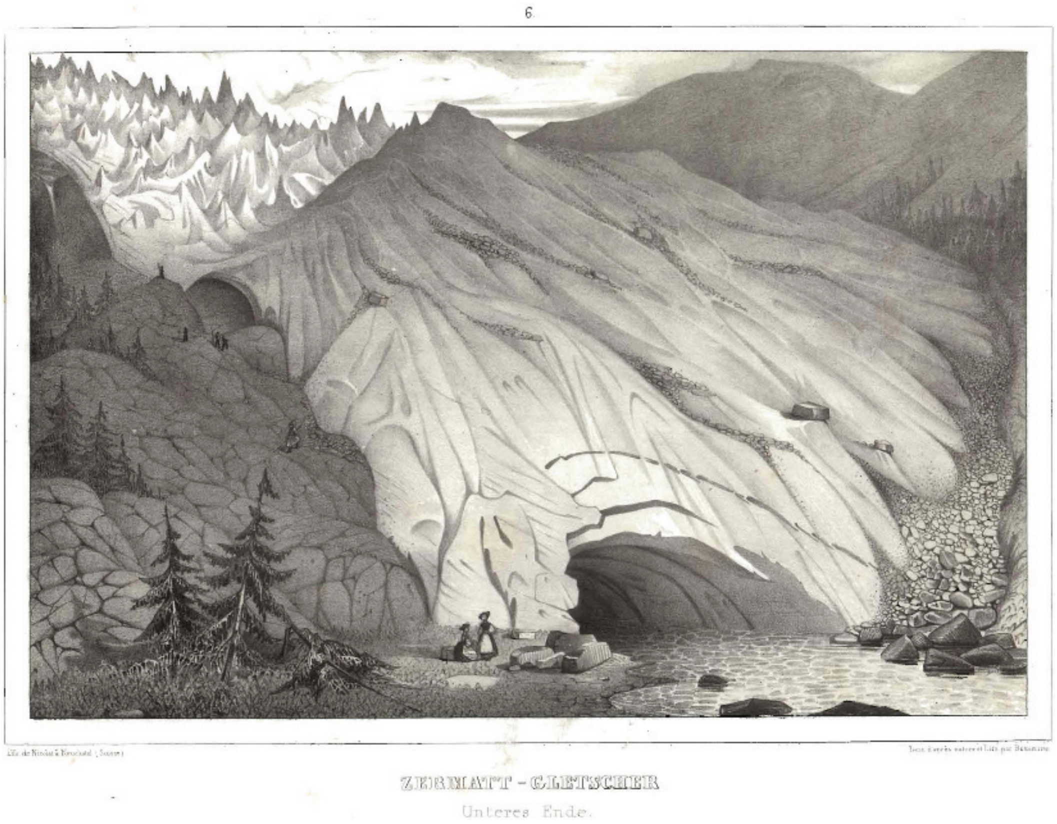


Figure 1.4 The lower end of the Gorner glacier (formerly called the Zermatt glacier). Neither of the two ladies at the foot of the glacier or the gentlemen on the adjacent rocks (left) seem to have work to do here; they are probably tourists. Source: Agassiz (1841).

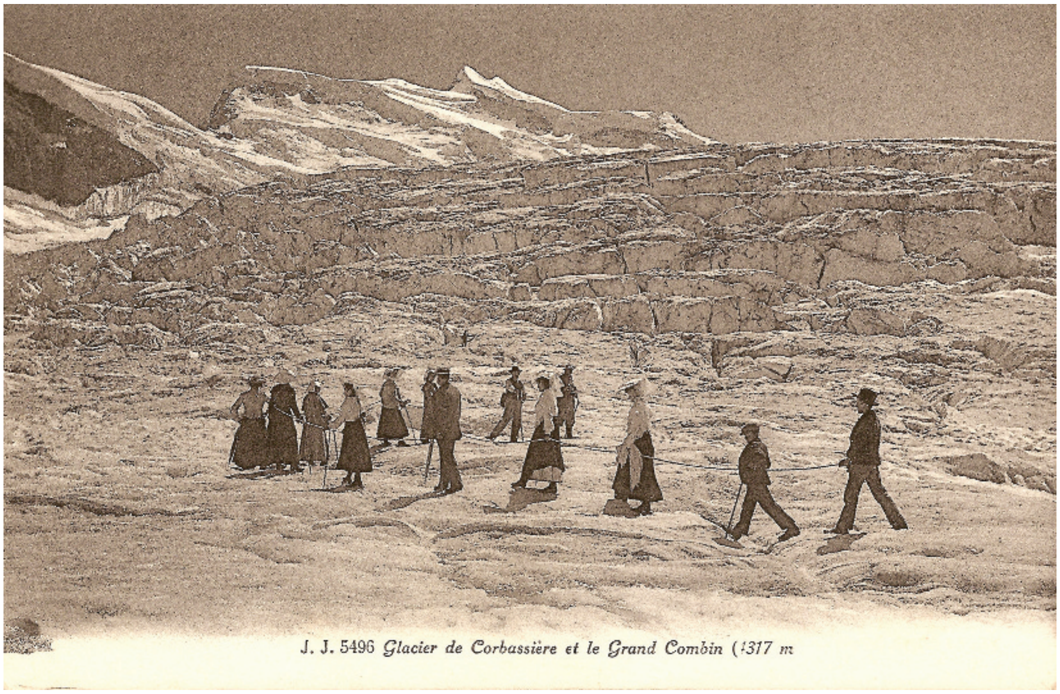


Figure 1.5 An excursion onto the Glacier de Courbassière, Valais, Switzerland. The nineteenth century saw a strong growth in tourism in Switzerland. The wild nature and the glaciers were not only major tourist attractions, but had also become more accessible for scientific research. From the point where 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.

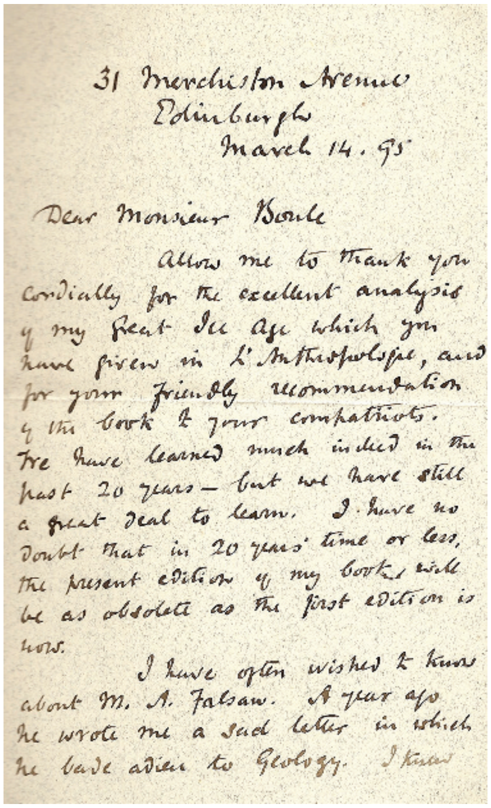
The following year (1880) Felix Wahnschaffe found glacial striae at several points on the northern edge of the German uplands. He wrote: 'In Velpke, some 5 km southwest of Oebisfelde, the surface of NE – SW trending almost horizontal sandstones which are overlain by boulder clay or glacial sand revealed 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 know

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).

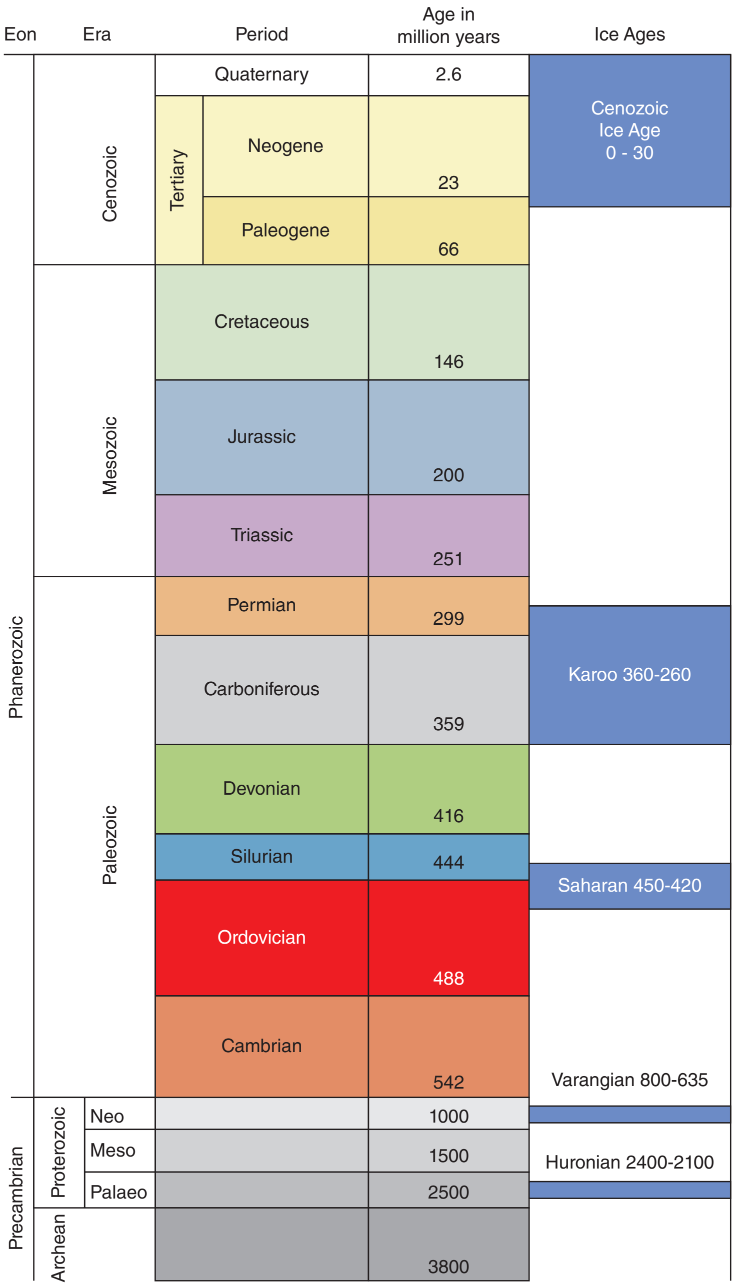


Figure 1.11 Geological timescale and the occurrence of ice ages in the Earth's history.

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.

Figure 1.13 Neoproterozoic tillite of the Varanger glaciation at Bigganjarga, Karlebotn, Varanger Peninsula, northern Norway. The tillite is part of the Smalfjord Formation, presumably upper Vendian (Varangerian) in age (>640 Ma). Photograph by Juha-Pekka Lunkka.

Figure 1.14 Neoproterozoic Port Askaig Tillite at the Port Askaig ferry terminal, Isle of Islay, Scotland. Photograph by Jürgen Ehlers.

BOX 1.3 QUATERNARY

The Quaternary Period is the youngest period in the Earth's history. It is characterized by cyclic phases of climate change, culminating in some cases in the growth and decay of continental ice sheets separated by warm climate events. In June 2009, the Executive Committee of the International Union of Geological Sciences (IUGS) formally ratified the new definition of the base of the Quaternary System/Period to the Global Stratotype Section and Point (GSSP) of the Gelasian Stage/Age at Monte San Nicola, Sicily, Italy. The base of the Gelasian corresponds to Marine Isotope Stage (MIS) 103, and has an astronomically tuned age of 2.58 Ma.

The Quaternary comprises two series: the Pleistocene and the Holocene. The Pleistocene is the geological series which covers the world's recent period of repeated glaciations. Consequently, the end of the last glaciation marks the end of the Pleistocene. This is easily said, but when exactly did the last glaciation end? Where do we find the geological record that allows us to draw a line at that position?

The Pleistocene–Holocene boundary is not defined in sand or clay or any other type of rock. It is differentiated in the NorthGRIP (NGRIP) core from the Greenland Ice Sheet. The boundary is reflected in an abrupt shift in deuterium excess values, accompanied by more gradual changes in $\delta^{18}O$, dust concentration, a range of chemical species and annual layer thickness. A timescale based on annual layer counting gives an age of 11,700 calendar years b2k (before AD 2000) for the base of the Holocene Series.

1.3 Causes of an Ice Age

We live in an ice age. Even if Europe and North America are recently almost free of substantial ice cover, today's 'warm stage' belongs to one of the colder phases of the Earth's geological history. The polar regions have been free of ice for the majority of the past, and the present temperate latitudes experienced a warmer climate than today.

The climatic fluctuations of the ice age are well known today as a result of investigations of deep-sea sediments, ice cores and sediment cores from inland lakes. The Pleistocene comprises 61 marine oxygen-isotope stages (MIS), representing approximately 30 cold and warm periods. Using palaeomagnetic studies, scientists have been able to date the sequence of cold and warm periods so accurately that the duration of the oscillations is known. During the last 600,000 years (600 ka), climate change was dominated by a glacial–interglacial cycle of approximately 100 ka; before that, shorter cycles of 40 ka prevailed. Today we know that those changes are largely controlled by the interplay of three cyclical variations of the Earth's orbit (Box 1.4; Fig. 1.15), including the eccentricity (100 ka), the angle of inclination of the Earth's axis (c. 41 ka) and the timing of the perihelion (c. 26 ka), which are causing changes in the incoming solar radiation (insolation).

BOX 1.4 EARTH'S ORBIT AROUND THE SUN IS NOT CONSTANT

Eccentricity of the orbit: The orbit of the Earth around the Sun is not a circle but an ellipse, the Sun located at one focus. The Earth's orbital parameters change under the influence of the other planets in our solar system. Sometimes it is almost circular, sometimes more elliptical. The changes occur over a cycle of *c.* 100 ka.

The tilt angle of the Earth's axis: The Earth's axis is currently inclined by 23.4° towards the plane on which the Earth moves around the Sun. The inclination angle varies over a cycle of *c.* 41 ka between 22.1° and 24.5°. A smaller axial inclination leads to cooler summers near the poles, so that the ice formed in the winter may not melt in the summer.

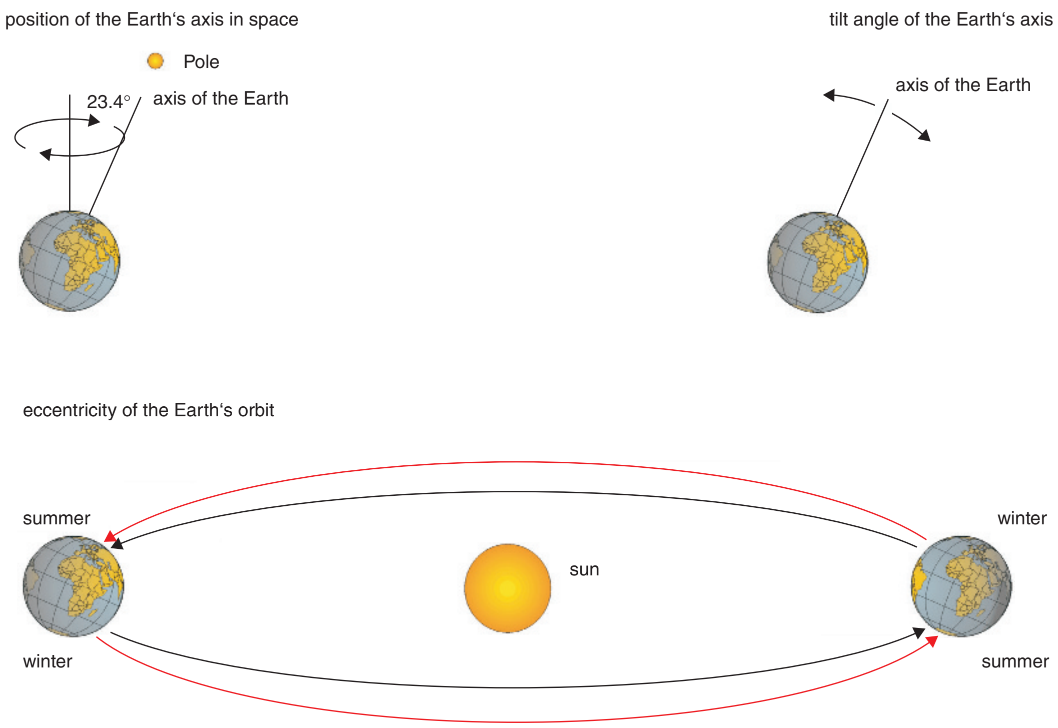
Precession: The position of the Earth's axis in space has not changed much. As the Earth orbits the Sun, its axis always points towards the north in the direction of the North Star. In the long term, however, the axis changes its position. In 12 ka it will point towards Wega (in the constellation Lyra). The precession cycle is *c.* 26 ka. This change means that the Earth reaches its closest point to the Sun in its orbit (the perihelion) in different seasons. The Earth currently reaches perihelion in winter.

The impact of these factors on the overall radiation budget of the Earth is small. A basic requirement of these orbital parameters eventually leading to climate change is that large landmasses are present near the poles; in the Southern Hemisphere, only permanently glaciated Antarctica is in a polar position. When the summers in the Northern Hemisphere are particularly cool (greatest distance to the Sun by the eccentricity, perihelion in summer) and the winters are warmest (minimum tilt of the Earth's axis), the northern continents are covered in snow for a long time. Snow has a greater reflection (albedo) than the ground, which contributes to further cooling.

This finding, which was presented by the Serb mathematician Milankovitch (1941), met initially with much scepticism. The fluctuations in the Earth's orbital parameters occurred throughout the Earth's history, whereas, according to contemporaneous knowledge, there had only been four ice ages. Only much later, when it turned out that the history of climate changes went back far beyond the traditional four ice ages, it became clear that the Milankovitch curve in principle was correct after all.

With the help of sensitivity analysis it has been shown that the astronomical parameters actually act as a pacemaker for the glacial–interglacial cycles. This can cause the climate cycles to be driven by solar radiation, but only at lower CO_2 concentrations. Long-term variations of the atmospheric CO_2 content alone are not sufficient to produce glacial–interglacial cycles. However, if both the orbital and CO_2 variations are considered in the model calculation, both point to the onset of the Ice Age at 2.75 Ma. The Early Pleistocene cycle of 41 ka, the transition to a 100 ka cycle at *c.* 850 ka and the glacial–interglacial cycles of the past 600 ka can all be almost exactly simulated (Berger & Loutre 2004).

Figure 1.15 The variations of the orbital parameters: (a) precession; (b) tilt of the Earth's axis; and (c) eccentricity.



The recent glacial–interglacial cycle of *c.* 100 ka is not only one of the most striking features of the Quaternary climate, but it also determines the future climatic development. Since each of the known climate cycles is characterized by a long cold period followed by a short interglacial (*c.* 10–15 ka), and as our interglacial (the Holocene) has already lasted for 10 ka, it might be suspected that the next glaciation is imminent. However, model calculations have shown that this is not the case. In the next tens of thousands of years, the Earth will have a nearly circular orbit around the Sun. This was also the case, for example, during MIS 11 at *c.* 400 ka before present, but not during the Eemian interglacial (MIS 5e; Berger & Loutre 2002). Accordingly, for the current interglacial a total length of *c.* 30 ka or more can probably be expected. The further increase of the concentration in atmospheric CO_2 by human activities may cause the Greenland Ice Sheet to melt and, within the next 10 ka, disappear completely. Further warming and not cooling is therefore expected.

The climatic cycles are only the 'pacemaker' (Hays et al. 1976), not the causes of the Ice Age. Schwarzbach (1993) suggests large changes in relief (mountain-building phases) as a possible explanation for the initiation of ice ages. Matthias Kuhle (e.g. 1985) was of the opinion that the glaciation of the highlands of Tibet had a significant impact on the global cooling of the Earth. Based on his field studies, he concluded that the snow line in High Asia during the Pleistocene ice ages had been lowered by around 1200–1500 m, so that an ice sheet of *c.* 2.4 million km^2 formed on the Tibetan Plateau. When High Asia had been uplifted far enough during the Early Pleistocene glacial cycles occurred repeatedly which, in conjunction with the radiation cycles, were sufficient to trigger large-scale global glaciations (Kuhle 1989).

Whilst Kuhle's ideas are controversial (see Sections 2.9.2 and 7.2) it is now undisputed that the relief of the continents has a major influence on global climate. Ruddiman & Kutzbach (1990) highlighted the significant role of the uplift of Tibet and the uplands in western North America on the general circulation of the atmosphere. However, model calculations indicate that this influence on the wind system is not in itself sufficient to trigger ice ages. The reduction of atmospheric CO_2 concentration, which was triggered by the increased chemical weathering of young exposed areas, has also been discussed as a possible cause of the ice ages (Raymo et al. 1988; Saltzman & Maasch 1990).

An important basic condition for the initiation of ice ages appears to be the distribution of large land masses. With the help of modern GIS technology, the former location of the continents and the rough shape of the Earth's surface can be reconstructed quite well. Extensive glaciation can only occur when appropriate land masses are present near the poles. During the Precambrian glaciations, almost all the continents were situated near the South Pole (Blakey 2008). During the Carboniferous glaciations, the southern continent Gondwana was in pole position (Stampfli & Borel 2004). The same applies to the Ordovician glaciation (Stampfli & Borel 2002). However, this also applies to the Devonian, an era for which no traces of glaciation have ever been found (Scotese 2008).

The shifting of the continents in the course of plate tectonics also caused changes in the ocean currents. The closing or opening of important straits has a significant impact on the oceanic circulation. The separation of Australia and South America from Antarctica and the resulting opening of the Tasman and Drake Passage during the Oligocene led to the isolation of Antarctica from warm surface water, forming the basis for the glaciation of that continent. The closure of the Straits of Panama during the early Pliocene stopped the currents running parallel to the equator, resulting in a rapid north–south exchange of water masses in the oceans, favouring glaciation of the northern continents (Smith & Pickering 2003).

Since the Earth has repeatedly undergone ice ages (during the Quaternary, Carboniferous/Permian, Ordovician and several times during the Precambrian), the question arises of whether a common timer can be found for these operations. Since these events seem to have been repeated roughly about every 250 million years, there might be a connection with the rotation of the galaxy. McCrea (1975) assumed that during each rotation the solar system had to pass through dust clouds in the spiral arms of the galaxy, meaning that the total irradiance was reduced; Dennison & Mansfield (1976) disagreed. The question of the common causes of the ice ages currently remains open. An overview of the many factors that may play a role is given in Saltzman's book *Dynamical Paleoclimatology* (2001).

The International Union for Quaternary Science (INQUA) was established in 1928, and exists to encourage and facilitate the research of Quaternary scientists of all disciplines. Five Commissions were established to focus on different fields of research: Coastal & Marine Processes; Humans & the Biosphere; Palaeoclimates; Stratigraphy & Chronology; and Terrestrial Processes, Deposits & History (Box 1.5).

BOX 1.5 INQUA

The International Union for Quaternary Research (INQUA) is the worldwide association of Ice Age research. It was founded on the Geographical Congress 1928 in Copenhagen. The initiative was started by Victor Madsen, then director of Danmarks Geologiske Undersøgelse, taking up a suggestion by Poland. Figure 1.16 shows only the central part of the official photograph of INQUA's founding fathers, which has been preserved in the Natural History Museum in Copenhagen. The names of the participants are listed on the back of the picture; most of the serious-looking men and women are completely forgotten today. The Germans include Paul Woldstedt (front row, third from left) and Rudolf Grahmann (diagonally right behind); on the other edge of the image the Hamburg Professor Gürich can be seen, easily identified by his white goatee. Austrian Gustav Götzinger, who would go on to host the third INQUA Congress in Vienna (1936), is in the centre (behind the man with the cigar). It is however striking that many important Quaternary scientists are missing; not a single North American was present.

Figure 1.16 Foundation of INQUA at the Geographical Congress in Copenhagen in 1928. Reproduced with permission of Kurt Kjær, Natural History Museum, Copenhagen.

INQUA was initially an European organization. Götzinger suggested at the second INQUA Congress in Leningrad to include the Americas and Asia in the future. The extension to a 'global association' was approved at the 16th International Geological Congress in Washington (1933); three years later in Vienna, as well as representatives of the European nations, there were scientists from Japan, the Dutch East Indies, Turkey, Mexico, Argentina and the first five scientists from the United States, a total of 193 participants (Götzinger 1938). The next INQUA conference was planned to be held in England (Cambridge) in 1940, but was sidelined for obvious reasons.

The international conferences have continued since after the Second World War to this day, and take place every four years. They provide scientists with the opportunity to present the latest research and exchange new ideas (Fig. 1.17). The number of participants has increased significantly; the XVIII INQUA Congress in Bern, 2011, saw some 2000 scientists in attendance.

Figure 1.17 Closing ceremony of the XVII INQUA Congress in Cairns in 2007. Photograph by Jürgen Ehlers.

Investigation of the Pleistocene ice age has led to considerable progress in recent decades. This is true not only for the highly technical disciplines of age determination, deep-sea exploration and the study of ice cores from Greenland and Antarctica. Even with regard to mapping the limits of the individual glaciations, the changes are enormous. The differences are nicely illustrated in Figure 1.18, which compares Flint's (1971) map of the northern European ice sheets with today's interpretation, based on the INQUA project 'Extent and Chronology of Quaternary Glaciations' (Ehlers et al. 2011a), which have itself been updated for this book.

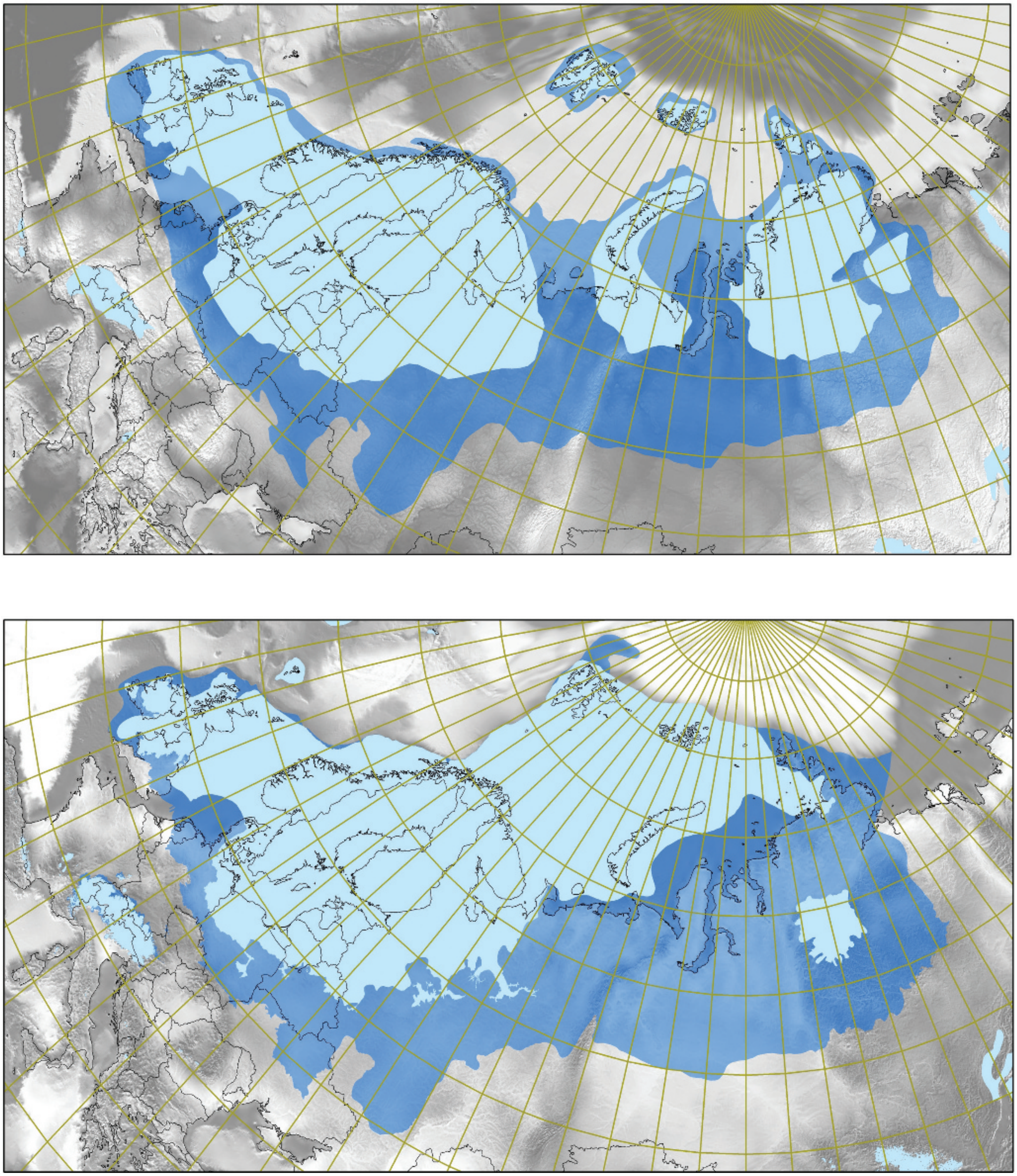


Figure 1.18 Comparison of the glacial limits during the Weichselian glacial maximum (light blue) and the maximum Pleistocene glaciation (dark blue) in northern Europe according to Flint (1971, above) and according to recent interpretations (2011, below). Map from Flint (1971) reproduced with permission of John Wiley & Sons.