Jürgen Ehlers

The Ice Age

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Foreword

Writing a book does not only mean spending many hours at the computer, but such an undertaking interferes with many aspects of daily life. In this case, for example, it led me one day in the summer of 2019 to stand in a well-known shop for comics and joke articles near the University of Hamburg and ask for something I assumed would be effortless to get. But the waitress shook her head, "A devil mask? No, we don't have anything like that."

Too bad. But there were numerous other things that had to be organised first. For example, many places had changed significantly over the years. These included the glaciers in Scandinavia and in the Alps. This also included the erratic block "Alter Schwede" in Hamburg, which suddenly looked completely different in January 2019. The only object that had not changed significantly was the dinosaur made of cement at Hagenbeck's zoo in Hamburg. Only our son, who served as a size comparison then as now, has changed. After all, there are more than 10 years between the two photographs.

There were many beautiful but also exciting moments during the off-road activity. For example, when my wife and I were wading around in the middle of a Swedish strand bog shortly before nightfall and in pouring rain and suddenly realised that we had lost our bearings. But it all worked out. And we also eventually got the devil's mask, by mail, along with a pack of fake blood. We couldn't use the blood.

To keep the book from becoming too anaemic, I have asked many friends and acquaintances, as I did for the first edition, to critically review parts of the manuscript and/or to provide me with illustrations:

- Sarah Abu-Anbar, Abu Dhabi
- Dr. Hinrich Bäsemann, Tromsø
- Dr. Christine L. Batchelor, Cambridge
- Toby Benham, Scott Polar Research Institute, Cambridge
- Prof. Dr. Margot Böse, Free University of Berlin
- Dr. Patrick L. Colin, Coral Reef Research Foundation, Palau
- Dr. B. Brandon Curry, Illinois State Geological Survey
- Dr. Jens Ehlers, Hamminkeln
- Prof. Peter Felix-Henningsen, University of Giessen
- Ingrid Ese Folkestad, Filmmakeriet AS, Larsnes, Norway
- Prof. Phil Gibbard, University of Cambridge
- Prof. Magnús Tumi Guðmundsson, University of Iceland, Reykjavi
- Dr. Alf Grube, Geological Survey of Hambur
- Dr. Robert Hebenstreit, Free University of Berlin
- Dr. Christian Hoselmann, Hessian State Office for Geology and the Environment
- Prof. Dieter Jäkel, Free University of Berlin
- Adriaan Janszen, TU Delf
- H.P. Kaufmann, Brunnen, Switzerland
- Dr. Kurt Kjær, Natural History Museum, Copenhagen
- Dr. Manfred Kupetz, Brandenburg State Environmental Agency, Cottbus Branc
- Prof. Kurt Lambeck, Australian National University, Canberra
- Dr. Tobias Lauer, Max Planck Institute for evolutionary Anthropology, Leipzig
- Marcus Linke, State Office for Geoinformation and Surveying, Hamburg
- Prof. Dr. Thomas Litt, University of Bonn
- Thomas Mielke, Hamburg
- Prof. Dr. Andrea Moscariello, University of Geneva, Switzerland
- Johan Petter Nystuen, University of Oslo
- Dr. Frank Preusser, University of Bern
- Prof. Vladimir E. Romanovsky, University of Alaska, Fairbanks
- Dr. Henrik Rother, Saxony-Anhalt State Office for Geology and Mining
- Prof. Gerhard Schellmann, University of Bamberg

- Prof. Christian Schlüchter, University of Bern, Switzerland
- Dr. Petra Schmidt, Witzeeze
- Gertrud Seehase, Ratzeburg
- Eva-Maria Stellmacher-Ludwig, Wentorf
- Dr. Hans-Jürgen Stephan, Kiel
- Klaus Stribrny, Thünen Institute, Trenthorst
- Dr. Klaus Steuerwald, Krefeld
- Dr. Þröstur Þorsteinsson, University of Iceland, Reykjavik
- Dr. Stefan Wansa, Saxony-Anhalt State Office for Geology and Mining
- Prof. Dr. Stefan Winker, University of Würzburg
- Gerda and Holger Wolmeyer, Hamburg
- Dr Jan Zalasiewicz, University of Leicester
- Prof. Bernd Zolitschka, University of Bremen

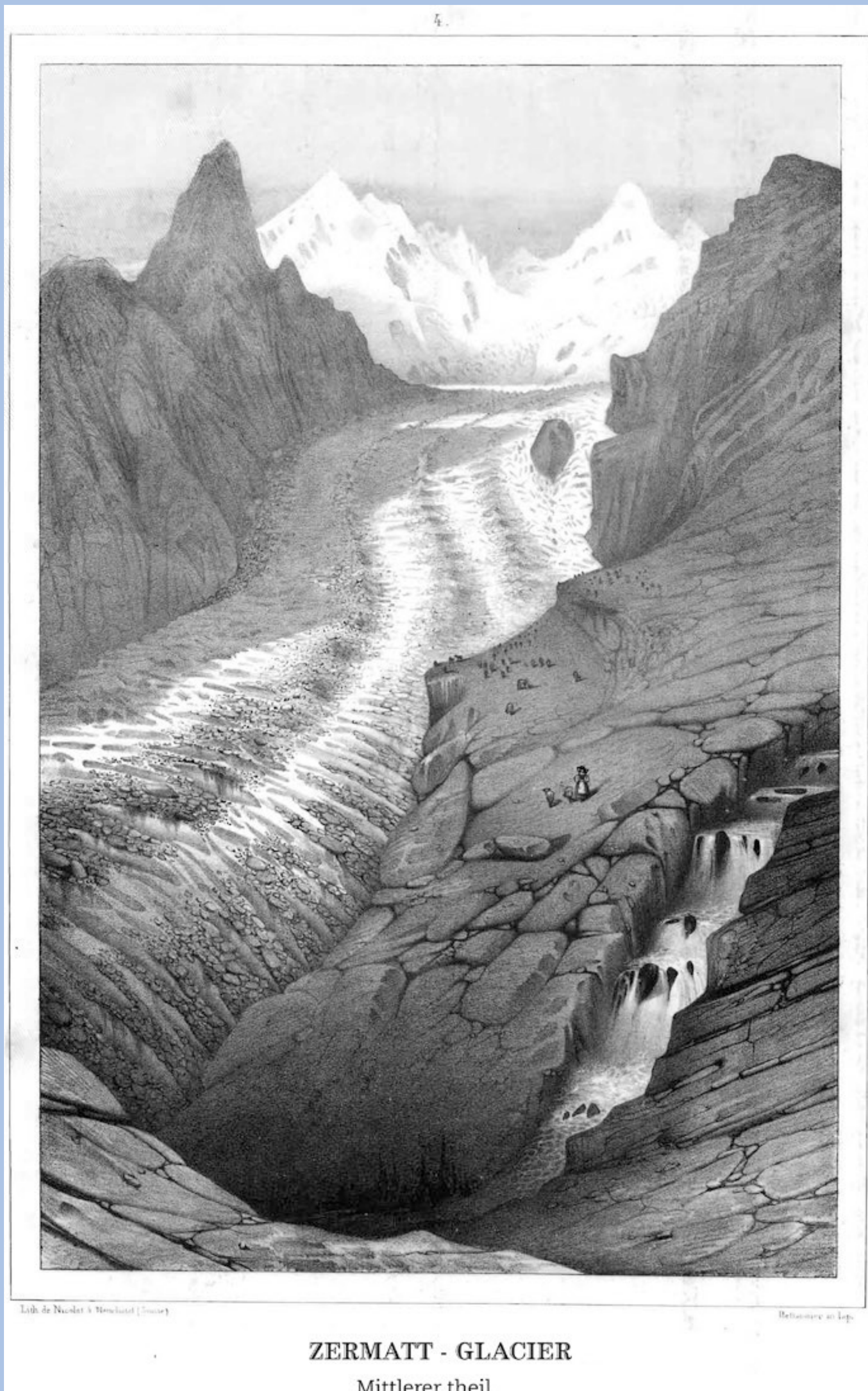
I would like to thank you all very much. And also the devil, of course.

It's supposed to be pretty hot in hell. The story with the mask ended, appropriately enough, with me standing in front of a glacial boulder in a thicket near Lyon on one of the hottest days of the year in a devil's costume and having my picture taken. The stone was called "Pierre de la mule du diable," and Albert Falsan, who first described it in 1877, drew the boulder, complete with devil and mule, for his book. We did not have a mule with us just then; so, all we had left was the devil. When finally everything was over and I could take off the mask again and returned to our car covered with sweat, the owner of a neighbouring lonely house was already waiting there, who explained to my wife and me in French that this was his property and that we were not allowed to park there. He showed us a piece of paper on which he had written our license plate number. We didn't need to do that. We knew our license plate number. Good thing the man didn't know he had just met the devil. We politely excused ourselves and drove away.

Jürgen Ehlers
Witzeeze, Germany
30.03.2020

Contents

Introduction



Zermatt glacier, Switzerland, middle part (from Agassiz 1841)

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Contents

The fact that there was an Ice Age at all is a relatively recent discovery. It began when, at the meeting of the Swiss Natural History Society in Neuchâtel on July 24, 1837, the young president of the society, Louis Agassiz, surprisingly did not talk about the latest results of his investigations on fossil fishes, by which he had become famous. Instead, he declared that the erratic blocks in the Jura (and around Neuchâtel) were legacies of a great glaciation. It was to take many years before this concept was internationally recognized.

» "The Ice Ages! One can hardly imagine today with what perplexity and perplexity this theory was received some 150 years ago. The very idea that huge walls of ice should have pushed across our landscapes from the north and swallowed everything provoked undisguised rejection." (Zalasiewicz 2009).

The meeting of the Swiss Natural History Society in Neuchâtel on July 24, 1837 began with a scandal. The young president of the society, Louis Agassiz, did not speak about the latest results of his investigations on fossil fishes, by which he had become famous. Instead, he decided to talk about the fact that the erratic blocks in the Jura (and around Neuchâtel) were put there by a great glaciation. This "Discourse of Neuchâtel" is considered the birth of the Ice Age theory (Imbrie and Imbrie 1986).

Agassiz was not the first to claim this, but the first serious scientist. His lecture met with icy rejection. And even on the subsequent excursion on July 26, where everyone could actually examine the evidence of earlier glaciation with their own eyes, Agassiz failed to convince his fellow experts. The Ice Age theory seemed stillborn.

1.1 In the Beginning Was the Flood

Humans tend to explain phenomena that are initially incomprehensible to them by means of known processes. The idea of "ice ages" was alien to the scientists of earlier centuries. On the other hand, it was known that in the course of the Earth's history extensive areas of land had been flooded by the sea time and again. So it seemed obvious to interpret the remains of the Quaternary period, especially the erratic blocks, as the results of a great flood. Didn't the Bible also speak of a devastating deluge? Traces of the flood were found in many places on Earth. Johann Friedrich Wilhelm Jerusalem listed some of them. He wrote:

» "But the greatest attention deserves the pointed southern shape of Africa and India, and all the large gulfs around the whole of Asia, from the Red Sea to Kamschatka, trending from south to north, which are the surest proof that the Earth must once have suffered a violent inundation from the south, which in turn is even more confirmed by the quantity of skeletons of large southern land animals found in Siberia". (Jerusalem 1774)

When Jerusalem published these lines, the unconditional belief in the literal meaning of the biblical texts was no longer given. Jerusalem, advisor to Duke Charles I of Brunswick-Wolfenbüttel, was one of the most important theologians of the German Enlightenment. He was an educated man, having spent years in Holland and England. In his interpretation of the Flood he includes the dead mammoths from Siberia. He is well aware that "fossilized sea-animals, like the horns of Ammon, spread over the whole Earth" could not have come from the biblical Flood. But a flood, a very, very big flood, that was still conceivable.At the beginning of the nineteenth century, only a few still believed that this was the biblical Flood. One of them, Reverend William Buckland from Oxford, in 1823 introduced the term "Diluvium"into stratigraphic nomenclature.

The French naturalist Georges Cuvier wrote:

» "In certain countries we find numerous large blocks of primitive rock spread over the surface of other strata, and separated by deep valleys or even marine inlets from the peaks and mountains from which they must have come. We must therefore necessarily conclude either that these blocks were thrown out by eruptions, or that the valleys (which would have arrested their transport) did not exist at the time of their transportation, or else that the current of water which transported them surpassed in its violence all that we can now conceive." (Cuvier 1827)

This oldest attempt at a natural explanation for the occurrence of the erratic blocks far from their source rock corresponds to the rolling stone or mudflow theory, which was advocated primarily by Leopold von Buch (1815), but also by Alexander von Humboldt (1845) and the Swedish physician and naturalist Nils Gabriel Sefström (1836). It was assumed that the erratic boulders had been transported by enormous masses of water, the so-called "petridelaunian flood". The reason for the release of such water masses, which were supposed to have flowed out of the Alps and the mountains of Scandinavia, had to remain open, of course.Von Hoff was the first in Germany to reject Cuvier's catastrophism in his *Geschichte der durch Ueberlieferung* nachgewiesenen *natürlichen Veränderungen der Erdoberfläche* (1834). Charles Lyell, in his *Principles of Geology* (1830–1833), had also spoken out against the decisive action of catastrophes. In those years, neptunists quarreled with plutonists; but the idea of a gentle reshaping of the Earth seemed to prevail.

A new interpretation of the erratic blocks emerged at the beginning of the nineteenth century. According to the drift theory, icebergs scraped the bottom of a shallow, cold sea and transported the erratic boulders (see box on drift transport).

1

Transport by Sea Ice

The sandstone block in Fig. 1.1 is 185 × 175 × 135 cm; its weight is estimated at 8 t. It lies on a salt marsh covered with *Spartina alterniflora.* When the stone was pushed landwards by drift ice during its deposition, it left a distinct furrow in the soil (foreground right).

Goethe had also heard that ice floes were supposed to have transported rock material from Sweden across the Øresund to Denmark. Was this how the erratic blocks of northern Germany had arrived at their present location?

Drift ice is actually capable of moving large rocks. The coastal waters of northern Canada are covered by ice in winter. In spring, the ice cover breaks up and the resulting ice floes drift along the coast. In this way, frozen rock and soil material can be displaced by drift ice (Fig. 1.2). The Canadian geographer Jean-Claude Dionne has discussed this phenomenon in numerous publications.

The image shows a melting ice floe that has torn a 25–30 cm thick layer out of the salt marsh and moved it seaward with the ebb current. Drifting icebergs create significantly larger scour marks. Corresponding *plough marks* from icebergs of the Weichselian Ice Age are found on the seafloor down to great water depths.

The supporters of the drift theory, which included Darwin and the physicist Helmholtz, still had to assume a greater extent of the glaciers to explain the occurrence

Fig. 1.1 Rocks transported by drift ice at l'Isle-Verte, St. Lawrence Estuary, Canada. (Photo: Jean-Claude Dionne)

Fig. 1.2 Stranded ice floe with a thick layer of soil frozen-on, St. Lawrence Estuary, Canada. (Photo: Jean-Claude Dionne)

of the numerous icebergs, but they rejected extensive glaciation. Lyell (1840) also discussed the origin of the erratic blocks in northern Europe and strongly opposed the neo-catastrophism envisaged by Agassiz.

Agassiz did not let up. In 1840 he published his book *Études sur les glaciers,* followed a year later by the German edition *Untersuchungen über die Gletscher.* Both books were printed at the author's expense. Alexander von Humboldt advised Agassiz that he should rather return to his fossil fish. "By doing so," he wrote, "you would do a greater service to positive geology than by these general considerations (which are somewhat glacial) on the upheavals of the primitive world, considerations which you yourself know only too well can at best convince those who put them into the world." (quoted in Imbrie and Imbrie 1986).

Agassiz nevertheless succeeded. He was able to show that the legacy of the glaciers extended from the present ice margins through series of terminal moraines into the Alpine foothills, and that the path of the stones could be traced from their area of origin to the outermost edge of their distribution. And he did not hesitate to publish his results not only in words but also in pictures. His elaborately designed atlas conveyed the views of its author more convincingly than many words.

Agassiz demanded considerable imagination from his readers. He wrote:

> "At the end of the geological epoch which preceded the rise of the Alps, the Earth was covered with an immense crust of ice which extended from the polar regions over the greater part of the northern hemisphere. The

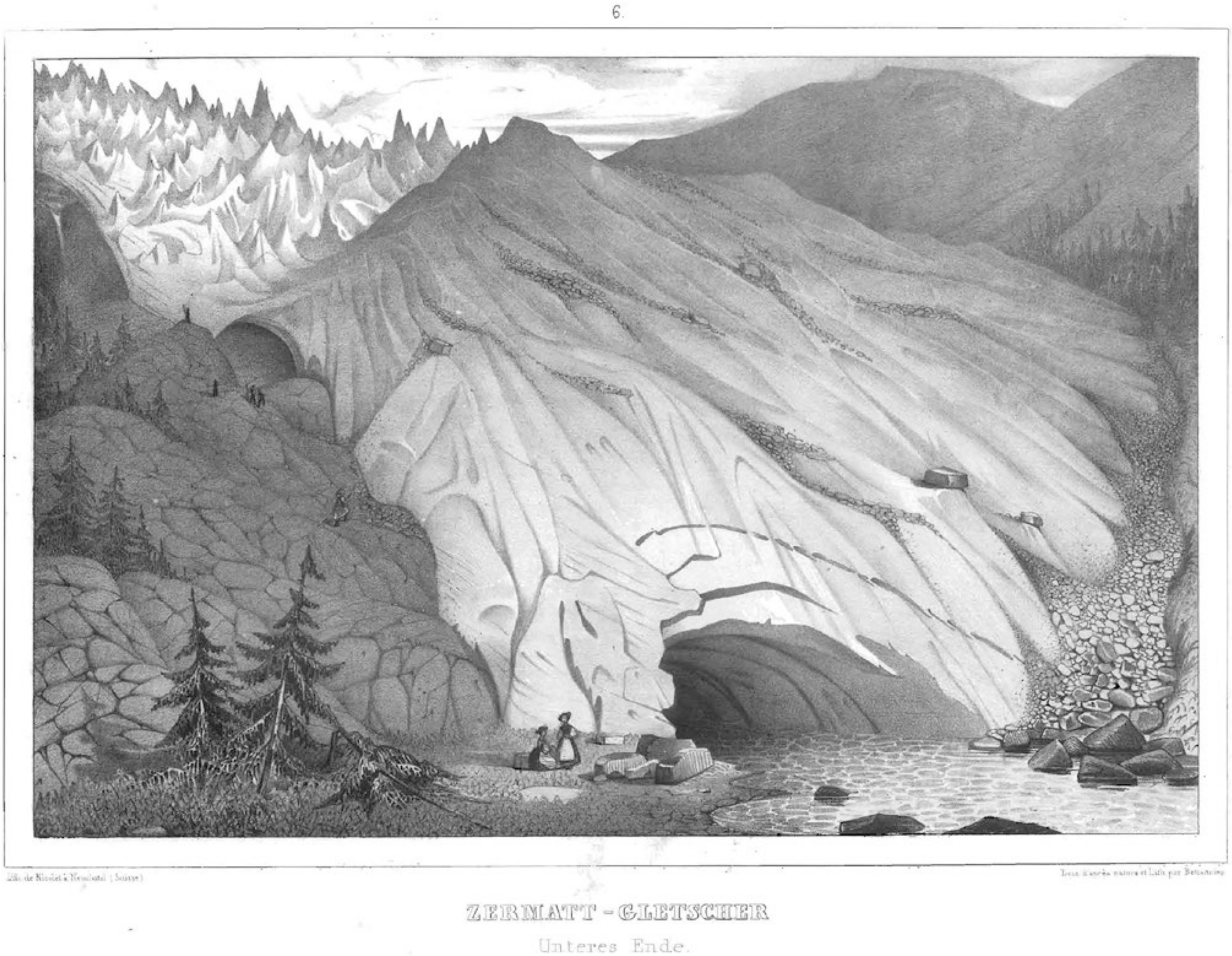


Fig. 1.3 Zermatt Glacier, Switzerland, lower end. (Agassiz 1841)

> Scandinavian and Great British peninsulas (sic!), the North and Baltic Seas, northern Germany, Switzerland, the Mediterranean as far as the Atlas, northern America and Asiatic Russia were an immense ice field, from which only the highest peaks of the then existing mountains (…) emerged." (Agassiz 1841, p. 284)

The scientific breakthrough came with his trip to Great Britain, where he finally succeeded in convincing William Buckland of his theory. Buckland in turn convinced Charles Lyell, the most important geologist of his time, and as early as November 1840 all three appeared together before the Geological Society of London to present their new findings to the scientific community. At first, the audience remained sceptical, but from now on the triumph of the Ice Age theory was unstoppable.The discussion also attracted a great deal of public interest. Switzerland and its peaks were one of the most popular destinations of the beginning tourism (Figs. 1.3 and 1.4). The first to be drawn to the Alps were mainly English mountaineers. In those early days, the journey was arduous; it was only in the last decades of the nineteenth century that the railway made the journey easier (Hachtmann 2007). The opening up of the Alpine region in terms of transport also made it easier for scientists to carry out their research on site. And also Norway's glaciers were no longer accessible only to a select few, such as the German emperor (box Nordlandreisen), but also to ordinary tourists since the Bergen Railway came into operation.

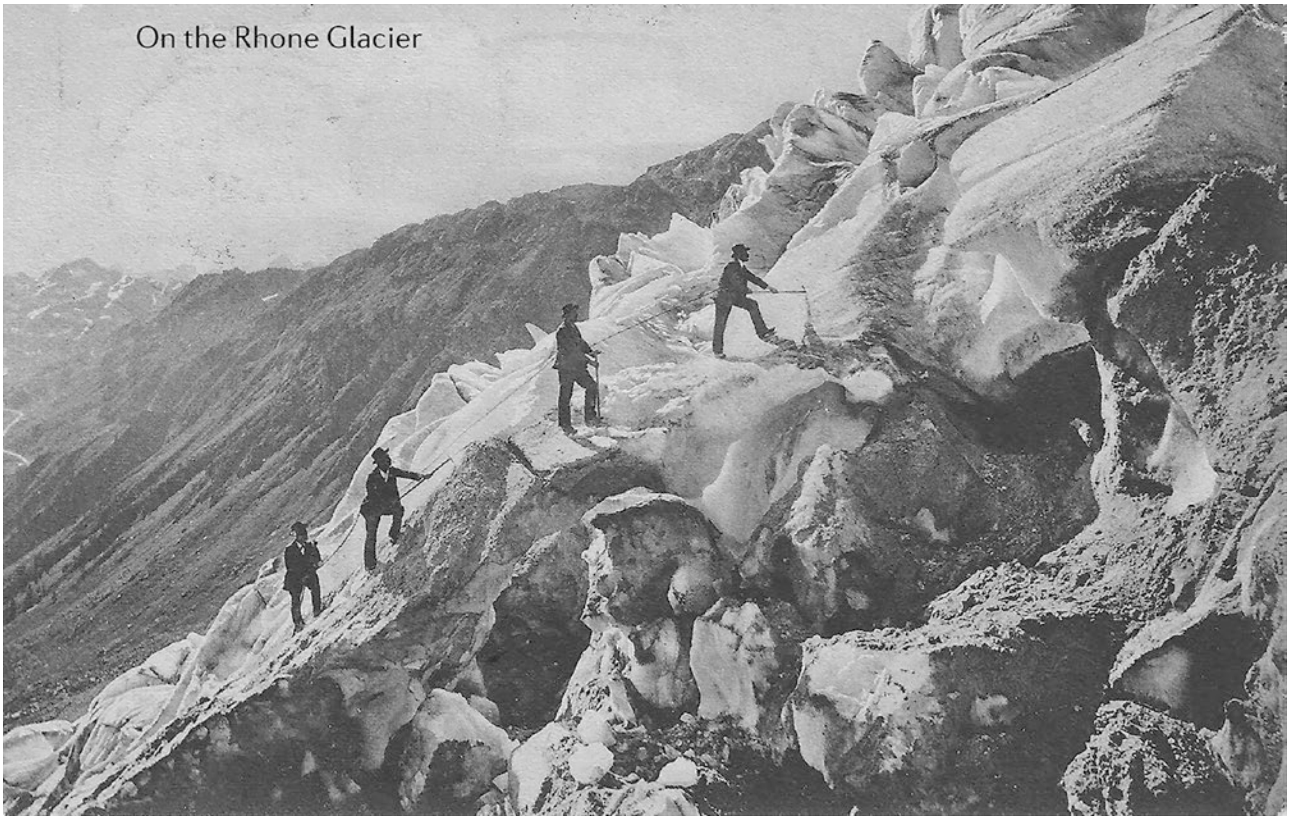


Fig. 1.4 An excursion to the Rhône Glacier, Switzerland. In the nineteenth century, tourism in Switzerland experienced a strong boom. The wild nature, and therefore also the glaciers, became interesting for tourists and also more accessible for scientific research. Since then the length of the Rhône Glacier decreased by 1632 m from 1879 to 2017. (GLAMOS 1801-2018). Postcard before 1907

Nordlandreisen

Kaiser Wilhelm II was a great friend of the Nordic landscape. In his imperial yacht "Hohenzollern", he undertook his first extended trip to the North Country just one year after taking office in the summer of 1889 (Fig. 1.5). A year later, the Emperor's programme included an excursion to Briksdalsbreen glacier. However, this undertaking was ill-starred. Already during the boat trip across the 11 km long lake Oldenvatn it started to rain, and in the following hours it rained without interruption. The excursion company changed into carriages at the end of the lake. Finally, the road climbed steeply, and then they stopped at a farmer's house, which could hardly accommodate the large number of guests. They had brought baskets of delicacies, but as it rained through the leaky roof into the living room, the mood was depressed. Some of the gentry decided to walk up to the glacier. The emperor stayed in the peasant's hut and returned to the "Hohenzollern" a little later.

The Emperor's travels meant that other people who could afford it also went to Norway in the summer to catch a glimpse of the Emperor and his entourage (Fig. 1.6). Kaiser Wilhelm felt very attached to Norway and the Norwegians. When a devastating fire in January 1904 almost completely destroyed the town of Ålesund, he immediately organized an extensive relief effort. Later he donated to Norway a 22 m high monumental sculpture of the legendary folk hero Frithjof, created by the German sculptor Max Unger. The inauguration ceremony in 1913 was attended by the Norwegian King Haakon VII, and there was a great popular celebration for several 1000 people. A year later, the emperor unfortunately had to prematurely abandon his 26th trip to the North Country at the outbreak of the First World War.

In northern Germany, the glacial theory gained acceptance particularly late. It is true that Charpentier (1842) had already claimed the existence of a northwestern European glaciation as far as England, Holland, the Harz Mountains, Saxony, Poland and "almost as far as Moscow". He could not, however, prevail with this opinion any more than Bernhardi (1832) before him or Morlot (1844, 1847) after him. Bernhard Cotta (1848) wrote:

Fig. 1.5 The imperial yacht "Hohenzollern" on the Nordland voyage 1911 off Balholm (today: Balestrand), Norway (Riksarkivet, Oslo)

Fig. 1.6 Party in the garden of the Norwegian painter Hans Dahl on July 13, 1911, Emperor Wilhelm in the centre (Riksarkivet, Oslo)

» "It exceeds the limits of the conceivable to suppose that glaciers reached from the Norwegian mountains to the Elbe and to Moscow, and even to the coasts of England, and move over this scarcely sloping but uneven ground, laden with moraines. (...) On the other hand, in both polar regions of the Earth, a kind of natural stone transport is known, which constantly takes place, and which may well be suitable to explain the northern debris of Europe and America, as well as the erratic blocks of Patagonia. That is the transport by floating ice-floes."

This drift theory prevailed and remained the doctrine in northern Germany for decades (e.g. Cotta 1867); see also box A proof of the drift theory?

A Proof of the Drift Theory?

At the end of the 1870s, Heinrich Otto Lang set out to get to the bottom of the question of glacial theory on the basis of the North German erratic blocks (Lang 1879). Lang was born 1846 in Gera-Untermhaus; he received his doctorate in 1874 and subsequently became a private lecturer in mineralogy and geology at the Universität Göttingen. When he heard that a large gravel deposit had been found in Bremen, near Wellen, he had Prof. Buchenau from Bremen and a Herr von der Hellen send him more than 180 stones, asking them not only to collect those rocks that looked particularly interesting, but above all those that "represented the essential constituents of the deposit".

Lang was faced with an almost insoluble task. His work was made more difficult by the fact that he had never been to Scandinavia, and that some of the authoritative literature was not accessible to him. On the other hand, he was able to draw on various geological collections, including the petrographic collections of the Königlichen Universität Göttingen, which contained erratic boulders from Coburg, Hanover, Loitz in Pomerania, Denmark, Sweden and Iceland. The Icelandic rocks will have been of little use to him, as were the rocks collected by the first German North Pole expedition.

Since the rocks could not be illustrated because of the high cost of printing, the only thing left to do was to describe them accurately. Lang took great pains:

» "A brownish-red granite (156) has as its primary constituents almost only feldspar and quartz; the feldspars form, so to speak, a red matrix in which grey quartz grains, which even appear black in section, are embedded as can be seen with the naked eye; other dark, duller, irregularly defined areas in section are found more sparsely; on a fissure surface, which at one point shows the opening of a cavern, there are in places hints of iron hydroxide or also of a light greenish, mica-like mineral, and it is this circumstance in particular that makes the rock resembling a granite boulder from Zeitz in Thuringia (Liebe's Priv.-Collection) ..." (Lang 1879)

Lang asked himself: Could these stones have been brought to northern Germany by the glacier? The answer was: No. It is well known that a glacier can only bring rocks that it has picked up in its area of origin. In the present collection, however, there is a great diversity of rock types, and this speaks against a glacial transport. In the case of transport by drifting icebergs, on the other hand, the mixing can be explained much more readily.

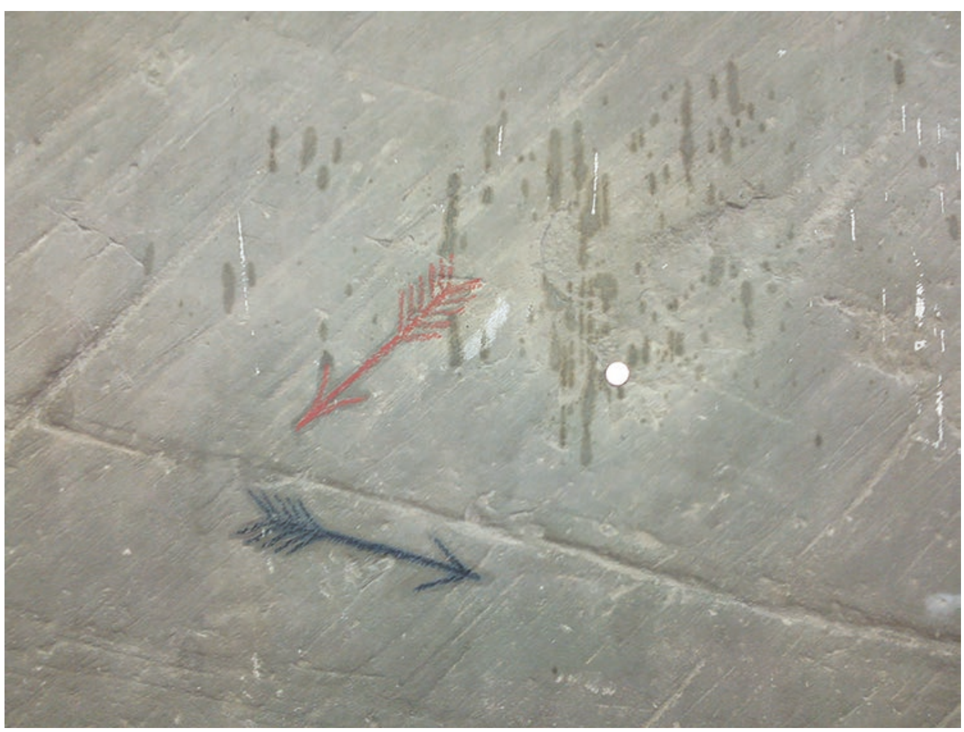
> Lang put a great deal of effort into it, and when his work was already in print, he supplied final additions as an appendix. In the meantime, a surprising opportunity had arisen for him to travel to Christiania (Oslo) and southern Scandinavia. There Lang found his views confirmed: There had been no ice age. He concluded with the joking remark: "One cannot spare Mr. Torell the reproach that he is playing with ice."
>
> But all the effort was in vain. In the same year Albrecht Penck's essay on "Die Geschiebeformation Nord-Deutschlands" (1879) was published, and with it the last doubts about the glacial theory were dispelled in the north of the German Empire as well.

When the Swedish geologist Otto Torell (on November 3, 1875), on an excursion in connection with a meeting of the German Geological Society in Berlin, clearly identified the striae on the Muschelkalk limestone of Rüdersdorf, already described by Sefström (1838) as glacial striae, a change of doctrine was long overdue. The glacial theory had already been firmly established in England and North America for ten years at that time (Lyell 1863, Dana 1863), and Torell had also published his views on the Ice Age in northern Europe as early as 1865. At first, only a few believed him.

In the following year (1880) Felix Wahnschaffe found glacial erratics at several points at the northern edge of the German low mountain ranges. He wrote: "Near Velpke, 5 km southwest of Oebisfelde, the sandstones, which strike from southeast to northwest, are overlain by boulder clay or boulder sand, under which extraordinary glacial striations were visible on the surface of the sandstone in several quarries." The glacial striae belonged to two different ice advances. The older striae, striking about 27°, were crossed by a younger set striking about 84°. A large slab of Rhaetian sandstone was recovered and deposited in the collection of the Royal Prussian Geological Survey. It can still be seen today in the collections of the Bundesanstalt für Geowissenschaften und Rohstoffe in Berlin-Spandau (◘ Fig. 1.7).

In Great Britain, James Geikie was one of the leading glacialists. In 1874 his book *The Great Ice Age and it's relationship to the antiquity of man* was published. Geikie was in contact with the leading geologists of his day, and writings and offprints were exchanged by mail. This, of course, included maintaining friendly contact with colleagues. Thus Geikie wrote: "Dear Monsieur Boule, Permit me to thank you warmly for the excellent analysis of my *Great Ice Age* in (the journal) *L' Anthropologie,* in which you kindly recommend the book to your countrymen ..." Of course, there was no harm in his immediately sending the good man a copy of the completely revised third edition (◘ Fig. 1.8).

In the foothills of the French Alps, naturalists set to work mapping the erratic boulders transported by the glaciers of the Ice Age. Albert Falsan, together with



◘ **Fig. 1.7** Rhaetian sandstone slab from Velpke (10 km OSO of Wolfsburg) with glacial striations running in two different directions. The slab is now in the collection of the BGR in Spandau. (Photo: Klaus Steuerwald)

Fig. 1.8 Map by Geikie showing the extent of the glaciers of the "Third Glacial Epoch" (i.e. Weichselian Glaciation) in Europe. The southern boundary of the glaciated area almost corresponds to the present state of knowledge. (From Geikie 1894)

Ernest Chantre, recorded the erratic blocks in the Rhône catchment area and documented the most conspicuous ones with small drawings (Falsan and Chantre 1877/78). The "Devil's Mule Stone" is one of the most striking specimens. It is located 1.5 km northwest of Artas. Science claims that the glaciers transported it there. However, oral tradition says it was the devil. Falsan accordingly depicted the devil in his drawing. And the devil was also present during our visit in summer 2019 (Fig. 1.9).

The second half of the nineteenth century also saw an awakening of interest in the origin of humankind. In 1859, Charles Darwin had published *On the Origin of Species by Means of Natural Selection, or The Preservation of Favoured Races in the Struggle for Life,* triggering a lively discussion among scientists and the public. Parts of his ideas were accepted very quickly (evolution, theory of descent), others, including the selection of species, only decades later. What had prehistoric man looked like? Geikie described the evidence, but he did not draw a picture. Others were less reticent. Dr. W. E. A. Zimmermann, for example, introduced his readers to *Die Wunder der Urwelt.* Subtitle: "A popular account of the history of creation and the original state of our world body, as well as of the various periods of development of its surface, its vegetation and its inhabitants up to the present time". There were no questions left unanswered (Figs. 1.10 and 1.11). Pictures showed, for example, "The Lisbon Earthquake" (smoke, flames, sinking ships). "Thirtieth Edition. Improved according to the latest standpoint of science" - however, the erratic blocks were still explained by drift ice transport in the 1885 edition.

1.2 The Ice Ages of the Earth's History

In other countries, there was already evidence in the mid-nineteenth century that the Pleistocene Ice Age had not been a singular event within the Earth's history. When people in northern Germany still believed in drift ice, traces of an older, Permo-Carboniferous Ice Age had been found in India (1856), Australia (1859) and South Africa (1868) (Fig. 1.12). Later (1871), evidence was found of an even earlier major glaciation phase, which had occurred during the late Precambrian in the so-called Vendian (600 million years ago). Today we know of an additional glaciation period at the end of the Ordovician (Hirnantian), the traces of which are probably confined to the Sahara. The first comprehensive overview of the Saharan glaciations was provided by Deynoux (1980). In addition, the existence of further, even older glaciation periods in the Precambrian about 950 million years ago and about 2000–2800 mil-

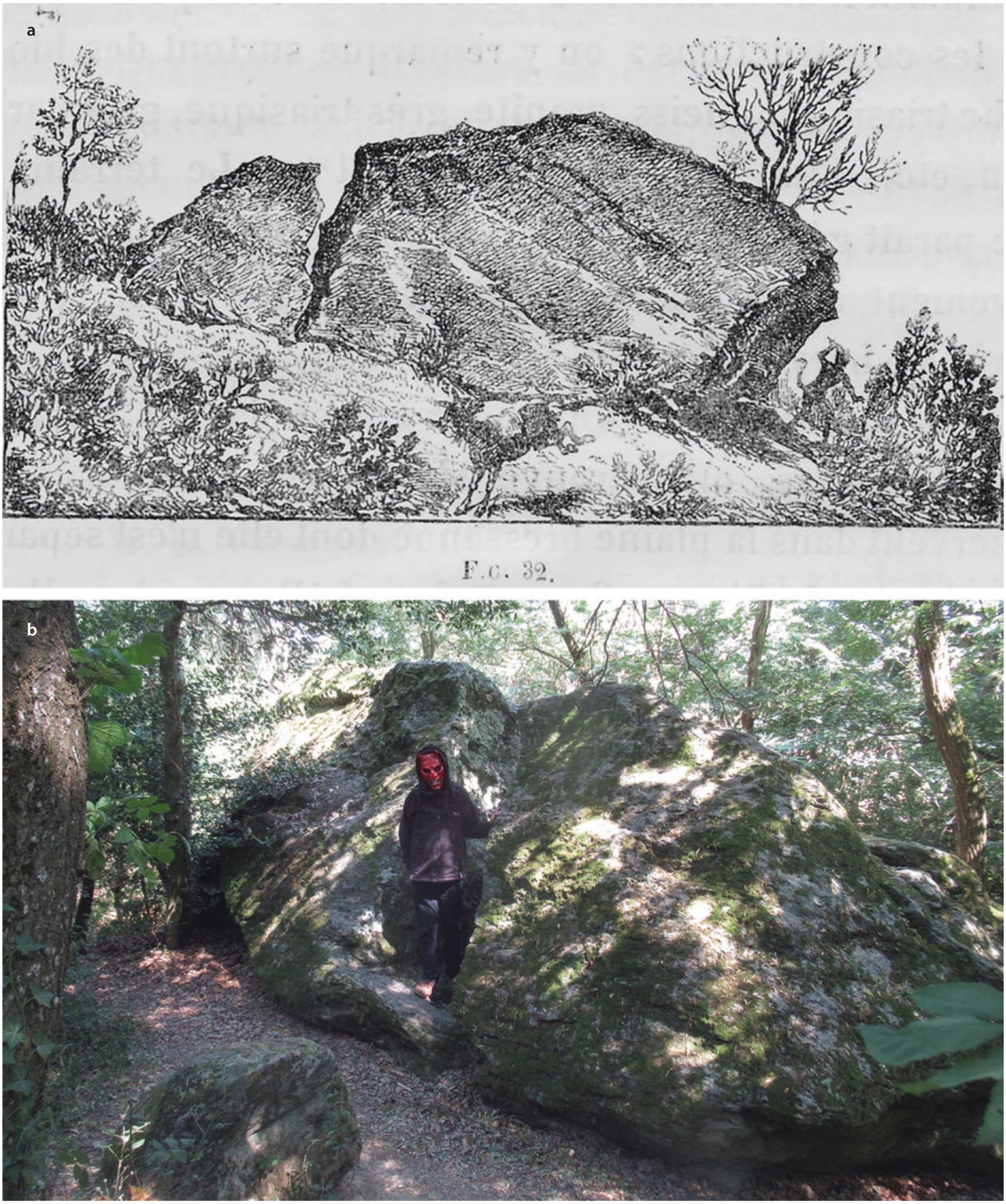


Fig. 1.9 **a** Albert Falsan, who among other things mapped the erratic boulders in the Rhône catchment area, made this drawing of the giant *Pierre de la Mule du Diable*. **b** The *Pierre de la Mule du Diable* today, devil for scale

Fig. 1.10 *Die Wunder der Urwelt* by Dr. W. E. A. Zimmermann (1885)

Fig. 1.11 Antediluvian man. Although the author makes fun in the text of the fact that someone presumes "to publish an illustration of our antediluvian ancestor", he reprints it all the same. (Zimmermann 1885)

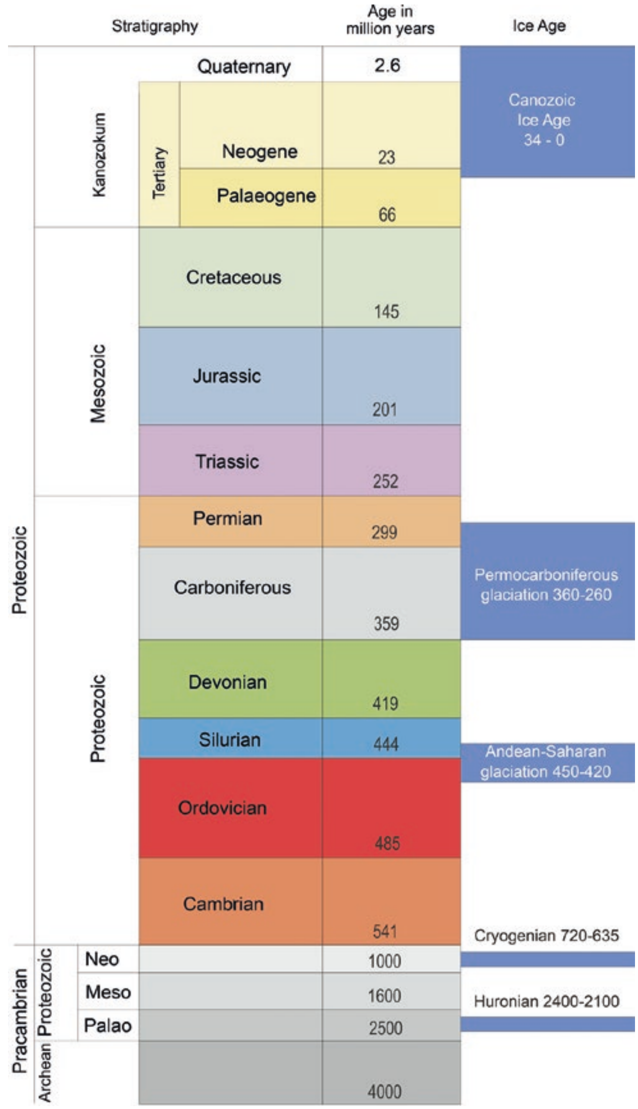


Fig. 1.12 Geologic time table (not to scale) and occurrence of Ice Ages in Earth's history. (After Cohen et al. 2019)

lion years ago are considered as certain (Hambrey and Harland 1981, Harland et al. 1990).

The longest lasting Ice Age began 2.4 billion years ago in the Paleoproterozoic (Huron glaciation). It lasted 300 million years. Whether the alternation between warm and cold periods known from later Ice Ages occurred during this period cannot yet be proven with certainty. This long-lasting Ice Age is seen in connection with the "*Great Oxigenation Event*" (Holland 2006). At the beginning of the Paleoproterozoic, the Earth's atmosphere contained high levels of methane but little oxygen. When cyanobacteria produced large amounts of oxygen as a waste product of their metabolism, it eventually accumulated in the atmosphere and oceans. This led to a mass extinction of anaerobic organisms that fell victim to oxygen's toxic effects on them. In the atmosphere, the now abundant oxygen oxidized most of the methane to CO_2 and H_2O with the help of UV radiation. However, since carbon dioxide has a much lower global warming potential than methane, global cooling set in and the climate remained at glacial levels for 300 million years.

The great glaciations are exceptional phenomena within the history of the Earth. The spatial distribution of glacial sediments from these geological eras is now fairly well known; however, the exact position relative to the pole and the exact age of the scattered deposits in many cases cannot be reconstructed with certainty. The only certainty is that many of the ancient glaciations were also multi-phase events.

In the tillite series of Scotland from the latest Precambrian (Port Askeig Formation), numerous layers of a stony diamicton (tillite) have been found. Glacial deposits from this time have also been found in many places on Earth, so that finally even the assumption arose that the Earth had been covered for a time by a kilometre-thick ice shield, which made any life impossible. The media, in particular, loved this sensational notion. However, evidence of such a "Snowball Earth" has not yet been convincingly established due to the limited outcrops and data available. These deposits, formerly called the Varanger Ice Age, are now part of the Cryogenian, a period of the Neoproterozoic that lasted from 720–635 million years before present (◘ Figs. 1.13 and ◘ 1.14, Nystuen and Lamminen 2011). During the Cryogenian there have been two extensive glaciations, the Sturtian and Marinoan glaciations. Tillites from these glaciations are also found in areas that were near the equator at the time - hence the notion of a "Snowball Earth". The overview map shows over 50 localities where corresponding glacial deposits have been found.

A glaciation at the end of the Ordovician has so far been proven in South America and in the Sahara (*Andean-Saharian Glaciation*). It lasted from 450 to 420 million years before present.

Traces of the Permo-Carboniferous glaciation are found widely on the southern continents (the former Gondwana). They are particularly well exposed in South Africa and the glaciation was therefore formerly called the *Karoo Glaciation.* The first traces of that glaciation date from the Devonian-Carboniferous boundary (Carmichaela et al. 2016). Extended glaciation, however, only evolved gradually. It reached its peak around 325 million years before present.

So far unexplained are the large fluctuations in sea level of sometimes more than 100 m at the transition from the Middle Jurassic to the Upper Jurassic. There is no evidence for the presence of any larger ice sheets at that time (Haq 2018).

These ancient deposits will not be further discussed here. The presentation in this book is limited to the most recent Ice Age of the Earth's history, the Quaternary.

1.3 Causes of the Ice Age

We live in an Ice Age. Even if Central Europe is currently free of ice sheets, today's "warm stage" is one of the cold phases of the Earth's history. The polar regions were free of ice for most of the time, and the present temperate latitudes had a warmer climate than today.

The climate fluctuations of the Ice Age are well known today due to investigations of deep-sea cores and sediments from inland lakes. Within the Pleistocene, 61 oxygen isotope stages can be distinguished, i.e. about 30 cold and warm stages each. With the aid of palaeomagnetic investigations, it has been possible to date the sequence of these cold and warm periods so precisely that the duration of the fluctuations can be determined. During the last 600,000 years, a cold-warm cycle of about 100,000 years dominated; before that, a shorter cycle of 40,000 years prevailed. Today we know that the interaction of three cyclical changes, namely the eccentricity of the Earth's orbit (100,000 years), the inclination of the Earth's axis (40,000 years) and the timing of the perihelion (20,000 years), cause changes in solar radiation (insolation) (◘ Fig. 1.15, box Earth's orbit). They must be regarded as the triggers of the cyclic climate fluctuations.

This finding, the main features of which had been presented by Milankovitch (1941), was initially met with scepticism. After all, the fluctuations of the Earth's orbital parameters had taken place during the entire history of the Earth, whereas according to the state of knowledge at that time there had only been four Ice Ages. Only much later, when it became clear that the history of climate fluctuations could be traced back far beyond the four classical cold stages, did it become clear that the Milankovitch curve was in principle correct.

■ **Fig. 1.13** Neoproterozoic Moelv tillite at Moelv on Lake Mjøsa, Norway; **a** general view, **b** detail. (Photographs: Hans Petter Nystuen)

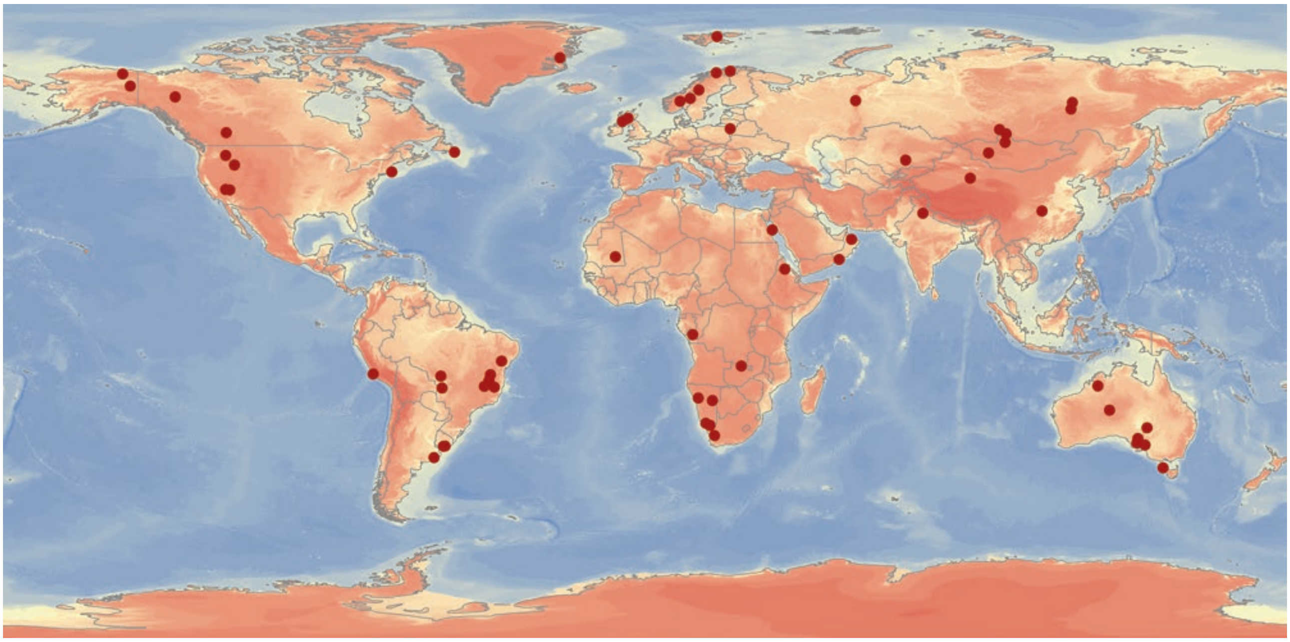


Fig. 1.14 Evidence of glacial deposits from the Cryogenian is found almost everywhere on Earth. However, it is by no means certain that they represent a snowball Earth. (According to data in Arnaud et al. 2011)

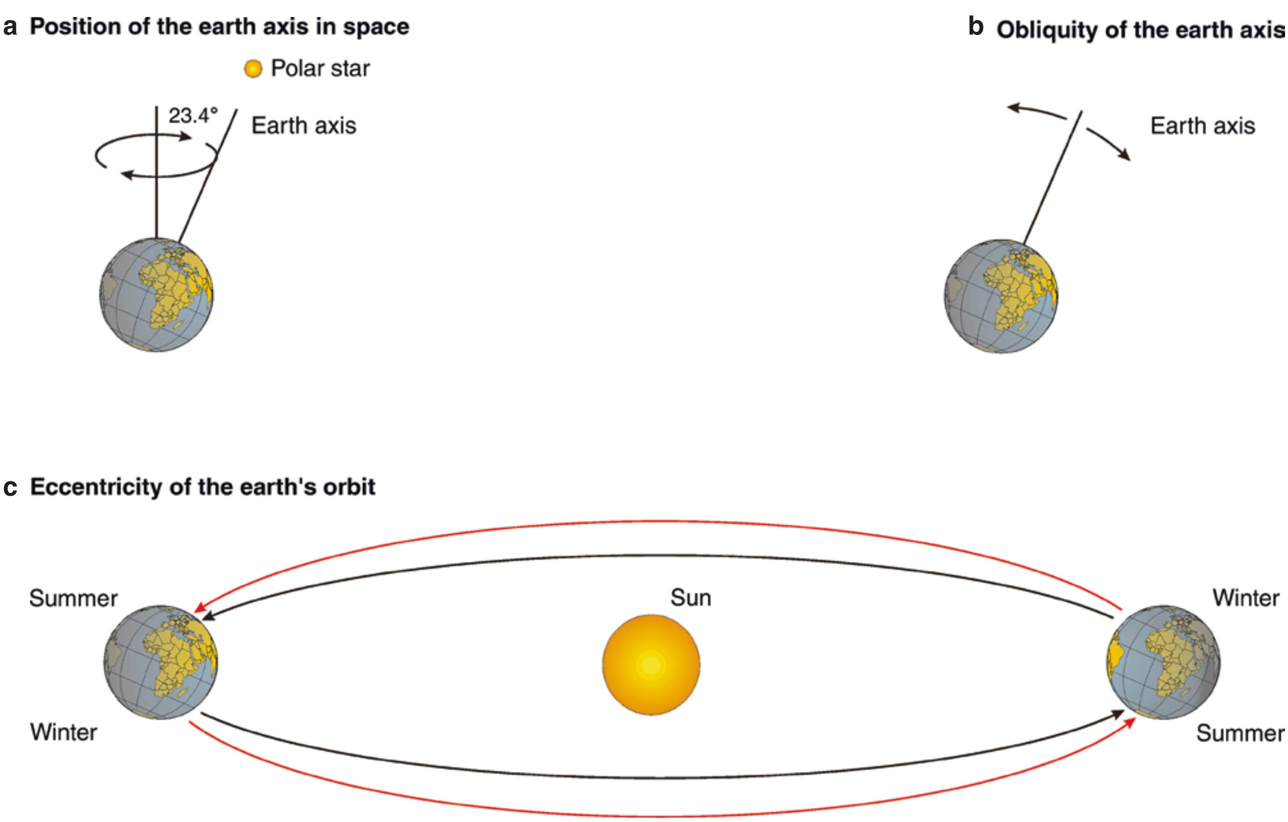


Fig. 1.15 The variations of the Earth's orbital elements: **a** precession, **b** obliquity, **c** eccentricity

The Orbit of the Earth Around the Sun is not Constant

Eccentricity of the Earth's Orbit: The Earth's orbit around the Sun is not a circle, but an ellipse with the Sun at one center of gravity. The Earth's orbit changes under the influence of the other planets in our solar system. Sometimes it is almost circular, sometimes more elliptical. The changes occur in a cycle of about 100,000 years.

The Tilt Angle of the Earth's Axis: The Earth's axis is currently tilted 23.44° from the plane on which the Earth moves around the Sun. The inclination varies between 22.1° and 24.5° in a cycle of about 41,000 years. A lower value results in colder summers near the poles, so that the ice formed in winter does not melt.

Precession: The position of the Earth's axis in space hardly changes. As the Earth orbits around the Sun, its axis today always points north, toward Polaris. In the long term, however, it will change its position. In 13,000 years, it will point to Vega (constellation Lyra). The cycle is about 25,800 years. This change causes the Earth to reach its closest point to the Sun in its orbit (the perihelion) at different times of the year. Currently, the Earth reaches perihelion in winter.

Effects: The effects of these factors on the Earth's radiation budget are small. A basic prerequisite for their being able to cause climate fluctuations at all is that in the northern hemisphere there are large land masses near the poles, whereas in the southern hemisphere there is only the permanently glaciated Antarctic. At the times when the summers in the northern hemisphere are particularly cool (greatest distance from the sun due to eccentricity, perihelion in summer) and when the winters are warmest (least inclination of the Earth's axis), the northern continents are covered with snow for longer periods. Snow has a greater diffuse reflection (albedo) than the Earth's surface, which contributes to further cooling.

With the help of sensitivity analysis, it has been shown that astronomical parameters do indeed act as pacemakers of glacial-interglacial cycles. In this context, the forcing by solar radiation can trigger the climate cycles, but only at low CO_2 concentrations. Long-term variations in CO_2 levels alone are not sufficient to produce glacial-interglacial cycles. However, when solar radiation and CO_2 fluctuations are included in the model calculation, it is shown that both the onset of the Ice Age around 2.75 million years before present, the Lower Pleistocene cycle of 41,000 years, the transition to a 100,000-year cycle around 850,000 years before present, and the glacial-interglacial cycles of the last 600,000 years can be simulated almost exactly (Berger and Loutre 2004).

The glacial-interglacial cycle of about 100,000 years is not only one of the most striking features of the Quaternary, but it also determines future climate development. Since each of the known climate cycles is characterised by a long cold period being followed by a short interglacial (circa 10,000–15,000 years), and since our interglacial, the Holocene, has already lasted for 10,000 years, one might think that the next Ice Age is imminent. However, model calculations have shown that this is not the case. The Earth will describe a roughly circular orbit around the Sun within the next few decades. This was the case, for example, during Marine Oxygen Isotope Stage 11 (MIS 11) about 400,000 years ago, but not during the Eemian Warm Stage (MIS 5e) (Berger and Loutre 2002). Accordingly, the current interglacial is likely to last about 30,000 years or more. Further increases in atmospheric CO_2 concentrations due to human activities are likely to result in further melting of the Greenland ice and its complete disappearance within the next 10,000 years, or even within the next 1000 years under unfavorable conditions (Gregory et al. 2004).

Consequently, climate cycles are only the "pacemaker" (Hays et al. 1976), not the causes of the ice age. Schwarzbach (1993) cites major relief changes (mountain building phases) as a possible explanation for the triggering of ice ages. Matthias Kuhle (e.g., 1985) believed that glaciation of the highlands of Tibet exerted a significant influence on global cooling during the Pleistocene. He assumed that the highlands of Tibet had been uplifted far enough during the Early Quaternary for glaciation cycles to occur which, in concert with radiation cycles, were sufficient to trigger large-scale glaciations worldwide (Kuhle 1989). However, the field evidence to date argues against large-scale glaciation of the highlands during the glaciation maximum of the last cold stage (Rother et al. 2017).

It is undisputed that the great relief of the continents has an influence on global climate. For example, Ruddiman and Kutzbach (1990) also point to the significant role that the uplift of Tibet and the highlands of western North America must have had on the general atmospheric circulation. However, model calculations suggest that this influence on wind systems alone is not sufficient to trigger Ice Ages. The lowering of atmospheric CO_2 levels caused by increased chemical weathering of young uplifted areas has also been discussed as a possible trigger of the Ice Age (Raymo et al. 1988, Saltzman and Maasch 1990).

An important basic condition for the triggering of ice ages seems to lie in the distribution of the large land masses on Earth. With the help of modern GIS technology, it is now possible to reconstruct the former position of the continents and the approximate appearance of the Earth's surface quite well. Extensive glaciations can only occur when major land masses are located near the poles. During the Precambrian glaciations, almost all continents were located near the South Pole (Blakey 2008). Also during the Permo-Carboniferous glaciation, the southern continent of Gondwana was in a polar position (Stampfli and Borel 2004). The same applies to the Ordovician glaciation (Stampfli and Borel 2002).

The shifting of the continents in the course of plate tectonics has not been without influence on ocean currents. The closing or opening of major straits has a significant impact on oceanic circulation. The separation of Australia and South America from Antarctica and the resulting opening of the Tasman Passage and Drake Passage isolated Antarctica from warm surface waters during the Oligocene and set the stage for the glaciation of this continent. In the early Pliocene, the closure of the Panama Strait disrupted ocean currents running parallel to the equator and led to a more rapid north-south exchange of water masses in the world's oceans, thus promoting the glaciation of the northern continents (Smith and Pickering 2003).

Since Ice Ages have occurred repeatedly in the course of Earth's history (in the Quaternary, the Carboniferous/Permian, the Ordovician and several times in the Precambrian), the question arises whether a common trigger for these processes can be found. A satisfactory answer to this question, which would apply to all known ice ages, cannot yet be given. An overview of the many factors that might play a role is given in Saltzman's book *Dynamical Paleoclimatology* (Saltzman 2001).

The INQUA

The *International Union for Quaternary Research* (INQUA) is the worldwide association of Quaternary scientists. It was founded at the Geographical Congress in Copenhagen in 1928. The initiative came from Victor Madsen, the director of *Danmarks Geologiske Undersøgelse,* who took up a suggestion from Poland. ◘ Figure 1.16 shows only a section of the photograph, which has been preserved in the Natural History Museum in Copenhagen. The names of the participants are noted on the back of the picture. Most of the serious-looking gentlemen and ladies are now completely forgotten. From the German side, Paul Woldstedt (front row, third from left, with glasses) and Rudolf Grahmann (diagonally behind on the right) were present; at the other edge of the group is Professor Gürich from Hamburg, recognizable by his white goatee. The Austrian Gustav Götzinger, who brought the third INQUA congress to Vienna in 1936, is found in the centre (behind the gentleman with the cigar in his hand). But it is noticeable that many important Quaternary scientists are missing. For example, there is no American.

INQUA was initially a European society. At the second INQUA Congress in Leningrad Götzinger proposed to include America and Asia. The extension to a "World Association" was approved at the 16th International Geological Congress in Washington in 1933, and in Vienna in 1936, apart from representatives of the European nations, scientists from Japan, from the Netherlands Indies, Turkey, Mexico, Argentina and for the first time 5 scientists from the USA were present. A total of 193 participants came (Götzinger 1938). In his farewell speech on September 22, 1936, Rudolf Grahmann concluded with the words: "I therefore conclude with the wish that our INQUA may continue to develop well like a good girl, that it may grow and prosper and take us in its arms again in a few years! Goodbye!" - The next INQUA conference was to take place in England (Cambridge) in 1940, but this did not happen.

The international meetings, which take place every four years, were continued after the Second World War. The 1982 meeting in Moscow (◘ Fig. 1.17) provided the first comprehensive insight into the state of Russian Quaternary research. The INQUA meetings present the latest research results and give scientists the opportunity to exchange ideas. The number of participants has increased significantly in the meantime. The 20th INQUA Congress 2019 in Dublin was attended by 2840 scientists.

Research into the Ice Age (see also box INQUA) has made considerable progress in recent decades. This applies not only to the highly technical disciplines of age determination, deep-sea research or the study of ice cores from Greenland and Antarctica. Even in recording the limits of glaciations, progress has been tremendous (◘ Fig. 1.18). The difference is illustrated by comparing Flint's (1971) map of the extent of northern European glaciation with the present-day representation, which is based on the digital map produced by the INQUA project Extent and Chronology of Quaternary Glaciations (Ehlers et al. 2011). It can be assumed that these will not be the last changes.

Fig. 1.16 Foundation of INQUA at the Geographical Congress in Copenhagen in 1928. (Source: Kurt Kjaer)

Fig. 1.17 Opening ceremony of the XI INQUA Congress 1982 in Moscow. (Source: INQUA)

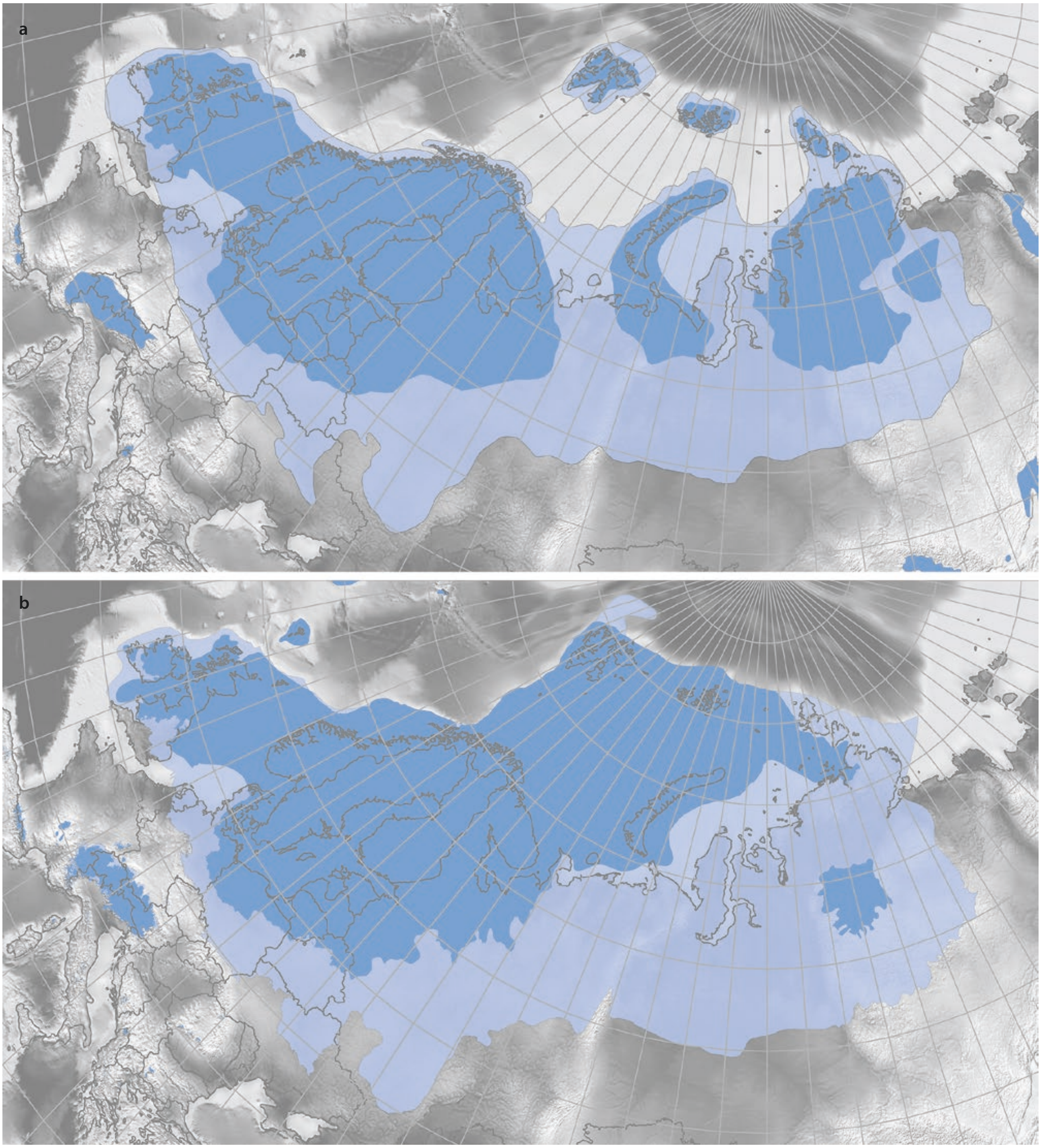


Fig. 1.18 Comparison of glaciation boundaries during the peak of the Weichselian Cold Stage in northern Europe (light blue) and the maximum Pleistocene glaciation (dark blue) between **a** the representation of Flint (1971) and **b** the present-day view. (Ehlers et al. 2011)

The Course of the Ice Age

Jan Mangerud explains the Eemian deposit at Fjøsanger near Bergen (Norway)

J. Ehlers, *The Ice Age*, https://doi.org/10.1007/978-3-662-64590-1_2

Contents

Even after many decades of research, there are still new things to discover. In the mid-1970s, organic deposits were found in Fjøsanger near Bergen that were quite obviously warm-stage layers. This was a minor sensation, because until then it had been assumed that all such deposits had been removed by the glaciers of the last Ice Age. The Quaternary geologists at the University of Bergen decided to examine the layers more closely. They were marine deposits from the last interglacial (Eemian warm stage) more than 115,000 years ago.

In the mid-1970s, organic deposits were found in Fjøsanger near Bergen that were quite obviously warm-stage layers. This was a minor sensation, because until then it had been assumed that all such deposits in Norway had been removed by the glaciers of the last Ice Age. The Quaternary geologists at the University of Bergen decided to study the strata more closely. In 1975/76, a 15 m deep pit was excavated down to the bedrock, 1 m below the present sea level. The rock showed glacial striations; it was overlain by till, which probably dates from the Saalian Stage. Above this followed sandy layers with mollusc shells. The shells belonged to a cold-water fauna. These layers were in turn covered by other marine deposits, whose fauna became more and more thermophilous towards the top, until finally a layer was reached when the sea had been at least as warm as it is today. As this layer was overlain by two other tills, it could only be deposits of the Eemian warm stage. This finding, reported by Jan Mangerud and his colleagues at the 1977 INQUA meeting in Birmingham, was later confirmed by detailed investigations (Mangerud et al. 1981). Even in such an obviously eroded landscape as the Norwegian fjord coast, older deposits in sheltered positions have survived being overridden by the ice of the Weichselian.

2.1 When Did the Quaternary Begin?

The beginning of the Ice Age does not represent an abrupt change in climatic conditions, but a gradual transition. ◘ Figure 2.1 shows that in parts of the Earth glaciers already existed in the Paleogene, while in other areas glaciations started much later. Consequently, the definition of the Neogene/Quaternary boundary must be more or less arbitrary, whereby different criteria are conceivable for the demarcation.

About 2.7 million years before today a considerable change can be seen in the sediments of the Lower Rhine area. At this time, the catchment area of the Rhine had extended southwards into the Alpine foothills, which was expressed in a drastic change in the heavy mineral composition (Boenigk 1982). Furthermore, at this time the thermophilous vegetation of the Pliocene was replaced by more cold-tolerant plant communities of the Quaternary. The gravel composition of the Rhine changed, and the mollusc associations also adapted to the cooler and more variable climate. Even if these changes did not all occur at exactly the same time, a clear change in flora and fauna can be observed during this period, accompanied by a change in sediment composition. In the Lower Rhine area, therefore, the Tertiary/Quaternary boundary was placed on the Reuverian/Praetiglian boundary at an early stage.

However, by decision of the International Geological Congress in 1948, the Tertiary/Quaternary boundary was defined as the base of the Calabrian (Italy). In the sediments of the Calabrium, cold-water indicators can be detected for the first time in the Mediterranean region (among others, the foraminifera *Hyalinea baltica*). The international Tertiary/Quaternary boundary was thus put at the upper limit of the Olduvai Event, a phase of normal magnetization within the reverse-magnetized Matuyama Epoch. In this way, the boundary was identifiable worldwide and also in fossil-free deposits. The position of this boundary was reconfirmed at the INQUA Congress in Moscow (1982). However, many Quaternary scientists were dissatisfied with it. This boundary meant that in North and South America, for example, there had also been extensive glaciations in the Pliocene. Efforts continued to correct the boundary - in the end with success.

2.2 What Is What in Stratigraphy?

In a sequence of rock strata, the oldest strata lie at the bottom and are overlain by successively younger strata. This rule, known as the "stratigraphic principle", was first formulated by the Danish scientist Nicolaus Stenonis (Niels Stensen) in 1669 (see box The stratigraphic principle).