1.1. INTRODUCTION

This new edition of Quaternary Glaciations—Extent and Chronology gathers together the evidence of glaciation from around the world in 77 chapters. The book combines all regions of the world into one volume and provides a closer look at the extents, timing, and wider significance of Quaternary glaciations. The main advances reported in this book include better understanding of the timings of glaciations—especially through the application of cosmogenic nuclide analyses—and better understanding of the detailed extent and subdivision of different glaciations. These advances are supported by new digital maps, the detailed production of which is presented below. In addition, this introduction summarises the compilation’s key findings and raises some of the main common themes that are apparent from the glacial records around the world. However, given the large number of excellent contributions, it is not possible to mention each chapter and it is recommended that readers explore the volume and discover for themselves the new findings from specific areas.

The editors would have liked to produce the volume in full colour. Unfortunately, that was not possible. However, this volume contains far more colour illustrations than the previous edition.

1.2. THE DIGITAL MAPS

For more than 150 years, geologists have mapped the traces of Quaternary glaciations. One main purpose of creating the maps is to obtain reproducible results. Where scale and coordinates are given, the results are considered to be reproducible. But different scales and different projections hinder comparison. In High Asia, for instance, the printed maps do not show much more than that there are very different views on that topic. However, where exactly the ice margins are supposed to be located is very difficult to reconstruct. True comparison is only possible where digital maps in a digital Geographic Information System (GIS) are employed.

At the INQUA Congress in Berlin 1995, a new investigation of the glacial limits seemed desirable. The last such attempt, coordinated by Denton and Hughes (‘The Last Great Ice Sheets’, 1981), was by that time almost 25 years old and much was out of date. During the congress, a working group on the Extent and Chronology of Quaternary Glaciations of the Commission on Glaciation was initiated. The first question that work group had to solve was to find a suitable base map. A scale of 1:1,000,000 seemed desirable. However, the printed World Map of that scale was compiled over a period of about 70 years (since 1913) and it was still incomplete. Fortunately, a digital map had become available just in time that seemed ideal for the purpose: the Digital Chart of the World (DCW).

1.2.1. The Digital Chart of the World

The DCW consists of 2094 tiles, each of which (except near the South Pole) is 5 x 5° in size. To identify the tiles, the globe had been subdivided into 12 latitudinal and 24 longitudinal stripes, named using the letters of the alphabet, starting from the south and the west. The resulting 15 x 15° areas were again subdivided into nine tiles, which were numbered. A tile named NK11 (Paris) would be between 0° and 15°E (letter N), between 45° and 60°N (letter K) and the southeasternmost tile of that section (number 11)—thus located between 0° and 5°E and 45° and 50°N (Fig. 1.1). Six hundred of these original tiles are required to cover the formerly glaciated parts of the globe. Gaps in the hypsometry layer of the DCW could be filled with information from the GTOPO30 terrain model (see below).
In 1999, when the coordinators of the project started to work with the DCW, the correctness of their base map was not in doubt. However, as soon as better digital maps got available, the shortcomings of the DCW became obvious. The horizontal accuracy was insufficient. The position of each individual line, point or polygon was found to be several hundred metres out of place, in extreme cases even more. At 1:1,000,000, where 1 km is equal to 1 mm, that is still acceptable. However, as soon as comparison with higher resolution topographic data is attempted, the error can no longer be tolerated. The present maps aim to be accurate at a scale of 1:250,000 (1 km equal to 4 mm). Freely available satellite-based topographic data have a much higher accuracy and allow mapping down to 1:75,000.

1.2.2. The GTOPO30 Terrain Model

The GTOPO30 terrain model had been compiled by the United States Geological Survey (USGS) in 1998 and can today be downloaded without charge from various websites. It has a horizontal resolution of ca. 1 km and is very suitable for overview maps, although at a scale of 1:1,000,000, it is at its limit. GTOPO30 was compiled from published sources. For most parts of the world, it is based on the Digital Terrain Elevation Data (DTED). Whilst the terrain model seems flawless in global overviews, at a higher resolution artefacts appear. One of them consists of diagonal stripes, especially in Africa and the Middle East. More disturbing is the dissolution of the image into $\frac{1}{2}$ blocks. This is strongest in areas of low relief, such as the lowlands of West Siberia. When used as an image, this effect can be masked by using the right altitudinal intervals. When trying to reconstruct the extent of the former ice-dammed lakes, however, the effects of this fault are clearly visible.

1.2.3. The Vector Map Level 1 (VMAP1)

Today, the DCW has been re-named Vector Map Level 0 (VMAP0), but the contents have not been updated. The VMAP1 is far more accurate, it is intended for a scale of 1:250,000. Unfortunately, only part of this comprehensive
map system, that like the DCW covers the whole globe, has been made available to the public. The published parts include most of the United States, about half of the Russian Arctic, parts of the Central Asian lowlands, Japan, parts of South America and a few other regions such as the Kerguelen Islands. For the present publication, the VMAP1 layers have been adjusted to the original DCW tiles format.

The VMAP1, like the DCW before it, is a map-based map. To create it, published maps have been digitised. This results in occasional ‘faults’ where adjoining map sheets do not match. There are also occasional gaps where either the published map was not available (for instance in minor parts of the former Soviet Union), or it was available but did not contain certain types of information (e.g. contours).

The VMAP1 dataset includes contours, although there is no altitudinal colouring. To make the information easier to read, the contours can be underlain by the ‘old’ DCW hypsometric tints.

1.2.4. GeoBase (Canada)

Additional topographic data and terrain models are available for several countries. For example, it is possible to download digital files of the Canadian terrain model (scale either 1:250,000 or 1:50,000) from GeoBase, as well as the roads, lakes, rivers and a few other layers without charge. The data have to be transformed to WGS84. The data come in 1° x 1° tiles. This means that for one tile of our digital maps, 25 tiles of the coarser version of the GeoBase terrain model are required. This makes the application of GeoBase possible for the present purpose, but very slow.

1.2.5. The Shuttle Radar Topography Mission (SRTM)

For most parts of the globe, the easier to use and higher resolution SRTM terrain model is available. It covers the area between 60°N and 60°S. It was created by radar measurements from the Space Shuttle in 2000. The data have undergone various corrections. The voids in the original coverage have been filled, the coastlines have been corrected and the surfaces of lakes and the sea have been levelled. The data are easy to download and to import into ArcView. They can be used to calculate contours, so that a highly reliable and very accurate base topography is available. The SRTM topography is good enough to show individual drumlins. However, because it is radar-based and largely uncorrected for contents, it shows forest areas as elevations. This can be seen nicely, when the SRTM model is combined with satellite imagery.

When trying to identify the glacial features shown in the maps, such as key sites, additional information is desirable. The river courses are visible in the SRTM terrain model, at least in hilly terrain, but there is no possibility to colour them blue, unless information from VMAP1 can be used. Lakes and rivers can be calculated from satellite imagery by isolating the black areas in infrared channel 4, but this method is very time-consuming and also hindered by cloud shadows and—more importantly—by shadows in narrow valleys.

1.2.6. The Open StreetMap

One possible additional source of information is the Open StreetMap (OSM). Particularly in densely populated areas such as in Central Europe, where no official topographic data are available without costs, the roads and coastlines and places given are a valuable source of information. And at a scale of 1:250,000, the OSM data are very reliable. The only problem is that the information is incomplete. In contrast to the several decades old data from DCW and VMAP1, the OSM is continuously updated. In some respects, this goes far beyond what is required in the current project (e.g. by including the street names). In other respects, however, it is still imperfect. Places like Hamburg, that are completely mapped, are the exception.

It should be kept in mind that where other (‘official’) data sources are available, such as in Canada, they may contain better quality information than the independent free sources.

1.2.7. The ASTER Terrain Model

In 2009, the altimetric data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument were made available to the public. ASTER is an imaging instrument on the Terra satellite launched in December 1999. On its sun synchronous, north to south path around the globe, it covers the whole world and through stereoscopic imagery that allows the construction of a terrain model. The nominal resolution is slightly better than that of the SRTM. Unfortunately, the images are marred by numerous artefacts—hills, holes and ‘mole runs’—which cannot be eliminated at present (Fig. 1.2). This misinformation is a major nuisance in regions such as the Arctic, where natural isolated hills (e.g. pingos), holes (e.g. thermokarst lakes) and ‘mole runs’ (e.g. eskers) are frequent. Therefore, the ASTER data have not been used in this project.

1.2.8. Printed Maps

Scanned topographic maps are freely available at various scales, especially for Canada (Geogratis Canada), the
1.2.9. Digital Maps: Conclusions

With the larger scale digital base maps used in the present publication, the accuracy of the information is increased by a factor of 16. The difference is striking (Fig. 1.3). Unfortunately, no single, uniform base map can be used at the 1:250,000 scale (Fig. 1.4). Therefore, in order to cope with the different levels of accuracy encountered, some of the layers of information have been grouped, so that only consistent information is shown together.

The SRTM terrain model, VMAP1 data and the OSM information are regarded as ‘true’ at a scale of 1:250,000. The DCW and GTOPO30 are only ‘true’ at the 1:1,000,000 scale. Some other layers of information, such as Art Dyke’s deglaciation maps of North America from the first edition of this work (Dyke, 2004), are only ‘true’ at 1:10,000,000 or even smaller scales.

In this publication, all the spatial data are given in shape-files to allow for easy import into other GIS systems. To take full advantage of the information collected in this project, a GIS is required. The authors are fully aware of the fact that not all readers will have ArcGIS at their disposal. To allow the non-GIS community a glimpse at the maps, some are available as KMZ files that can be read using Google Earth. Nevertheless, the user must be aware of the fact that those files are only images, and their contents are restricted to what has been selected by the author.

The authors hope that the current map set will be widely used, and that it will form the basis for further investigations.
FIGURE 1.3 Comparison of the digital maps from the first edition, based on the Digital Chart of the World, with a digital map from the present edition, using the SRTM terrain model.
FIGURE 1.4 The different base maps used in the present volume.
1.3. THE GEOLOGY

1.3.1. Prelude to the Quaternary

The initiation of conditions that resulted in Quaternary (Pleistocene and Holocene series) glaciation resulted from the long-term declining cooling trend in world climates that began early in the previous Tertiary Period. Apart from some limited activity in the Eocene both in the southern and northern hemisphere (Stickley et al., 2009; Ingólfsson, 2004; Tripati et al., 2005), significant glaciation began in the late Oligocene (ca. 35 Ma) in eastern Antarctica (Ingólfsson, 2004). It was followed by mountain glaciation through the Miocene (23–5.3 Ma) in Alaska, Greenland, Iceland and Patagonia, and later in the Pliocene (5.3–2.6 Ma) in the Alps, the Bolivian Andes and possibly in Tasmania (see respective chapters in this book). From the Neogene, glacially derived ice-rafted debris is found in ocean-sediment cores from the North Atlantic region, including the Barents Sea (Moran et al., 2006) and areas adjacent to Norway, northern and south-eastern Greenland, Iceland and northern North America, and in the Southern Ocean off-Antarctica.

1.3.2. Glaciation During the Quaternary

Since the recognition in the mid-nineteenth century that glaciers had been considerably more extensive than at present, the Quaternary has been synonymous with glaciation of the mid-latitudes. Today evidence from both the land and ocean-floor sediment sequences demonstrates that the major continental glaciations occurred repeatedly over what are now temperate regions of the Earth’s surface. Extensive ice-rafting, an indication that glaciers had reached sea level, is found from the earliest cold stage (2.6–2.4 Ma) in both the North Atlantic and North Pacific oceans (cf. Haug et al., 2005). Extensive glaciations were not restricted to the high latitudes. In Africa, Pleistocene glaciations were common to many mountains over 4000 m a.s.l. in the East African mountains such as Mount Kilimanjaro, Mount Kenya and the High Atlas. Glaciations also occurred on much lower mountains, such as in Algeria where large glaciers formed on mountains as low as 2300 m a.s.l. ( Chapter 76). Thus, Pleistocene glaciation was a global affair—with significant presence in the tropics as well as the mid- and high latitudes.

The climatic variations that have characterised the Earth’s climate during the late Cenozoic and indeed before are controlled by variations of the Earth’s orbit around the Sun which affects the receipt of solar energy at the Earth’s surface. These Milankovitch variations, named after their discoverer, are responsible for the cyclic climate changes that characterise the Quaternary and indeed much of Earth’s history. One of the most critical ways they are expressed is through the development of ‘Ice Ages’ or periods when glaciation extended across large areas of the Earth. The Early Pleistocene (2.6–0.8 Ma) was characterised by climatic fluctuations dominated by the 41 ka precession cycle, during which relatively few cold periods were sufficiently cold and long to allow the development of substantial ice sheets. Only 14 of the 41 cold stages of that period display evidence of major glaciation (Ehlers and Gibbard, 2011). They include the Plio-Pleistocene boundary events Marine Isotope Stage (MIS) 104, 100 and 98, together with Early Pleistocene MIS 82, 78, 68, 60, 58, 54, 52, 36, 34, 30 and 26 which reach 18Oocean% of ca. 4.6–5. It is not until the transition in dominant orbital cyclicity to the 100 ka cycles, that began ca.1.2 Ma and was fully established by about 800 ka (‘mid-Pleistocene transition’ Tziperman and Gildor, 2003), that the cold periods (glacials) were regularly cold and long enough to allow ice sheet development on a continental scale, outside the polar regions. However, it is during MIS 22 (ca. 870–880 ka) that the first of the ‘major’ cold events reached critical values of ca. 5.5 or above 18Oocean% equivalent to substantial ice volumes that typify the glaciations of the later Pleistocene (i.e. MIS 16, 12, 10, 6, 4–2). Potentially, therefore, it is likely that there were a minimum of 20 periods during which extensive glaciation could have developed during the past 2.6 million years, with the most extensive (ca. 5–6 periods) being limited to the last 900 ka (Gibbard and Cohen, 2008) In fact, recent findings imply that significant glacial expansion even occurred during MIS 14 (Chapter 17 and Giraudi et al., 2010).

Precisely where these glaciations occurred and how far they extended is very difficult to determine, given that the remnants of less extensive early glaciation tend to be obliterated and mostly removed by later, more extensive advances. Although this is so in all terrestrial areas, it is especially difficult in mountain regions where the preservation potential of older sequences rapidly diminishes with time and subsequent glaciation. However, examination of the frequency of glaciation through the Cenozoic indicates that glaciation in the southern hemisphere having been established first, principally in Antarctica and southern South America, occurred continually from the early Neogene to the present day (Ehlers and Gibbard, 2008). By contrast, northern-hemisphere glaciation, although initially somewhat restricted, increased markedly at the beginning of the Quaternary, increasing again in frequency in the latest Early Pleistocene and reaching very high levels in the Middle to Late Pleistocene. Whilst this pattern is not unexpected, the striking increase in ice sheets through the Quaternary clearly emphasises that worldwide glaciation is in effect a northern-hemispheric phenomenon.

1.3.3. Plio-Pleistocene Glaciation

Evidence of glaciation is widespread from throughout the Quaternary and indeed the Neogene in the northern Hemisphere. The longest sequences are restricted to Alaska, and
the adjacent North-West Territories of Canada which, together with Greenland and the Rockies, preserve evidence of glaciation from the Neogene to the present. In northern Canada and Alaska, the oldest till and accompanying ice-rafted detritus in marine settings date from the Early Miocene, with regionally widespread glaciation occurring in the Pliocene and regularly throughout the Pleistocene (cf. Haug et al., 2005; Chapter 32). In adjacent British Columbia, a comparable sequence is found, particularly in the north (Chapter 44). Similarly, in Greenland and Iceland, glaciation began in the Miocene, occurring regularly through the Pliocene and onwards to the present day in the mountains (Chapters 50 and 16). Likewise, in Norway, its adjacent offshore and the neighbouring Barents Sea, glaciation is recorded from the Early Miocene, Early Pliocene and Plio–Pleistocene (Knies et al., 2009; Chapters 22 and 27). In the Rockies of the United States, a much shorter glacial sequence occurs, although a Plio–Pleistocene-aged till is known from California (Chapter 34). In Europe, glaciation before the Middle Pleistocene is generally represented only by ice-rafted material, outside the mountain regions (e.g. in the Netherlands, lowland Germany, European Russia and Britain) (Chapters 7, 13, 20 and 26).

In the southern hemisphere, glaciation is much longer established, as noted above. Here the ice already formed in the Late Eocene—Early Oligocene in East Antarctica (Ingólfsson, 2004; Tripati et al., 2005; Miller et al., 1987) and built-up in a step-like pattern through the Neogene. The present polar conditions were already established by the Early Pleistocene after 2.5 Ma (Ingólfsson, 2004). A similar history is known from the Piedmont areas of Argentina and Chile, where substantial ice caps were established by 14 Ma (Heusser, 2003; Rabassa, 2008). Till deposits interbedded with basalt flows indicate the occurrence of glaciation even before the Pliocene–Pleistocene boundary (ca. 2.6 Ma) and widespread lowland glaciation became established between 2.05 and 1.86 Ma (ca. MIS 68–78), followed by the ‘Great Patagonian Glaciation’ that took place at 1.15–1.00 Ma (ca. MIS 30–34) (Chapters 51 and 52). Further north, there is little documented evidence of tropical Andean glaciers from the Plio–Pleistocene. It is estimated that the tropical Andes have attained most of their present elevation only during the past 5–6 Ma. However, the earliest glaciation recorded in the Bolivian Andes dates from at least 3.25 Ma (Chapter 56). Further, in Colombia, the first glaciations are dated to near the Gauss/Matuyama magnetic reversal at 2.6 Ma (Chapter 58). The earliest records in Australasia are found in New Zealand from the Plio–Pleistocene (2.6 Ma: MIS 98–104; Chapter 75).

1.3.4. Early and Middle Pleistocene Glaciations

The ‘glacial’ Pleistocene effectively begins with extensive glaciation of lowland areas, particularly around the North Atlantic region, and the intensification of global cold period (glacial) climates, in general. It coincides with the ‘middle Pleistocene transition’ (1.2–0.8 Ma) when the 100 ka Milankovitch cycles became dominant and caused the cold periods to become sufficiently cold for long enough to allow the development of continental-scale ice sheets.

The till sheets of the major glaciations of the ‘glacial Pleistocene’ are found throughout Europe. In northern Europe, till sheets characterise large areas of the lowlands and they are also found at the floors of the adjacent seas (Chapters 3, 6, 7, 8 and 9). New investigations have revealed to what a large degree the North Sea floor was shaped by repeated glaciation (Chapter 21). Further south, in central and southern Europe, till is restricted to the mountains and piedmonts (Chapters 2, 4, 11, 15, 17 and 24). In northern Europe, widespread lowland glaciation began in the early Middle Pleistocene shortly after the Brunhes/Matuyama palaeomagnetic reversal (780 Ka). The phases represented include the Weichselian (Valdaian, MIS 4–2), Saalian (Dniepr and Moscovian, MIS 6, 8 and 10), Elsterian (Okan, MIS 12) and the Donian (Narevian, Sanian, MIS 16). More limited glaciation may also have occurred in the circum-Baltic region during the latest Early Pleistocene (MIS 20 and 22). The evidence for Early Pleistocene glaciations in this region is restricted to Latvia (Chapter 18), Poland (Chapter 23) and possibly Lithuania (Chapter 19), although current research in central Jylland, Denmark, may also reveal evidence for pre-Cromerian glaciation in this area (Chapter 5). Curiously, evidence for early Middle Pleistocene glaciation is absent from the North Atlantic and Norway, whilst it is certainly present in Denmark, the Baltic region and European Russia. In the Italian Dolomites, glaciation becomes established in MIS 22 (Muttoni et al., 2003). Comparable evidence is also found from north of the Alps in Switzerland and southern Germany (Chapter 14). Further to the west, in the Pyrenees, the oldest glaciation identified is of late Cromerian age (MIS 16 or 14) (Calvet, 2004). Widespread lowland glaciation again is first seen in North America in MIS 22 or 20 (Chapters 32 and 49). From this point onwards, major ice sheets covered large regions of the continent during the Middle Pleistocene pre-Illinoian events MIS 16, 12, 8 and 6 (Illinoian s.s.) and the Late Pleistocene MIS 4–2 (Wisconsinan). In Mexico, the oldest moraines on volcanoes have been dated at 205 to 175 ka and probably correspond to an advance early in MIS 6 (Chapter 61). Evidence from East Greenland suggests that the southern dome of the ice sheet may have almost disappeared during the Eemian Stage interglacial (ca. MIS 5e). However, dating of the basal ice in the Dye 3 ice core has shown that ice has been present over this locality since at least MIS 11 (Chapter 50).

According to Chinese investigations, glaciation of Tibet and Tianshu is not recorded before the Middle Pleistocene, of which the MIS 12 glaciation was the most extensive. Four discrete Pleistocene glaciations have been identified.
on the Qinghai-Tibetan Plateau and the bordering mountains. These four main Pleistocene glaciations are correlated to MIS 18–16, 12, 6 and 4–2. This apparently delayed glaciation of the Himalayan chain might reflect late uplift of high Asia. The Kunlun Glaciation (MIS 18–16) was the most far reaching. Subsequent glaciations have been successively less extensive, probably caused by increasingly arid climates resulting from the progressive Quaternary uplift of the plateau (Chapter 70). On the contrary, Kuhle (Chapter 68) maintains that the last glaciation was most extensive when he envisages an ice sheet covered Tibet. However, this is increasingly a minority view, especially the concept that the Qinghai-Tibetan Plateau was almost entirely covered by an ice sheet. Many workers rigorously maintain that Pleistocene glaciations over the Qinghai-Tibetan Plateau were much more restricted (including Chapter 70; cf. numerous references in Lehmkuhl and Owen, 2005). Indeed, these authors argue that it is now generally well established that a large ice sheet did not cover the Tibetan Plateau. Nevertheless, this book provides both sides of the argument for this particular region and indeed for several other parts of the world where there is debate over the glacial history.

As in Europe and North America, glaciation increased in intensity throughout the South American Andes from 800 ky to the present day. In the northern Andes, there is some evidence of glacial deposition prior to the Late Pleistocene glaciations in Venezuela and Colombia (Chapters 59 and 58). However, in the southern Andes, Late Pleistocene glaciations were less extensive than during the Early Pleistocene events (Chapters 51, 52 and 54). Both easternmost Tierra del Fuego and the Falkland Islands are thought to have remained largely unglaciated during the Pleistocene (Clapperton, 1993), though there are traces of glacial scouring (Ehlers and Gibbard, 2008). In Australasia, following a 1 Ma break, the glacial record continues in MIS 12, followed by MIS 6, 4 and 3. In Tasmania, the earliest Pleistocene ice advances are thought to have been about 1 million years old but may be older. Middle Pleistocene ice advances occurred during MIS 10, 8 and 6 (Chapter 74). The presence of glaciations in this area during MIS 8, revealed by cosmogenic exposure dating, is interesting because a record of glaciation during this interval is lacking in many other parts of the world.

The succession of glaciations in MIS 16, 12, 6 and 4–2 is striking in that it is repeatedly found in numerous areas of the world, and the absence of records of glaciations during MIS 18, 10 or 8 probably reflect the fact that later glaciations were more extensive. However, it is possible that glaciations during MIS 18, 10 and 8 were, in fact, more widespread than currently realised simply because many dating techniques provide minimum ages for glacial deposits and landforms. This is true for U-series dating of cemented moraines (Chapter 15) and also when applying cosmogenic nuclide analyses to date ‘ancient’ surfaces (e.g. Chapter 74). Lack of precision when dating glaciations of the Middle Pleistocene and earlier in terrestrial settings means that some uncertainty will remain despite the development of better dating techniques. It is likely that the application of multiple methods of developing glacial geochronologies will be required in order to gain greater precision, and, crucially, to test the validity of the various dating techniques (cf. discussion in Chapters 55 and 57).

1.3.5. Late Pleistocene Glaciations

During the last glacial cycle of the Late Pleistocene, the extent of the glaciation of the Southern Hemisphere differed very little from that of the Pleistocene glacial maximum. Glaciers in Antarctica still reached to the shelf edge, and in New Zealand, Tasmania and South America, the glacier tongues were only slightly smaller than during earlier events (Chapters 51, 74 and 75). On mainland Australia, local mountain glaciation occurred (Chapter 74). In many parts of the Northern Hemisphere, glacial ice reached an extent very similar to the Quaternary glacial maximum. In North America, the differences are very small. Again, most parts of Canada were ice covered, including the shelf areas (Chapter 48). It is the same in Greenland (Chapter 50) and Iceland (Chapter 16). In many of these areas, ice reached maximum extents close to the trough of global ice volume recorded in the marine isotope record (ca. 21 ka). This is instructive because it involved the largest ice masses on Earth at the time: the Laurentide and Antarctic ice sheets.

In Europe, and on mid-latitude mountains around the world, however, the situation was different. New evidence suggests that the North Sea was not fully glaciated during the Weichselian glacial maximum but slightly earlier during MIS 4 (Chapter 21). A similar situation has been invoked for the southern Irish Sea area of the British Isles (Bowen et al., 2002), although recently, several studies have presented evidence that contradicts this view (e.g. Ó Cofaigh and Evans, 2007; Ballantyne, 2010). Further north, over the Barents Sea, glaciation during MIS 4 was more extensive than the later Weichselian glaciations (Fig. 1.5). During the Late Weichselian, an ice sheet covered the Barents Sea and extended well into the Kara Sea but hardly touched the Russian mainland and did not reach onto the Severnaya Zemlya islands (Chapter 27). In glaciated mountain areas outside the major ice sheets, such as in Italy and Greece, the maximum Middle Pleistocene glaciations were sometimes markedly greater extent than the local last glacial maxima (Chapters 15 and 17). This is attributed to a change in equilibrium-line altitude (ELA) because it has a much bigger impact on glacier size in areas characterised only by mountain glaciation than in areas where ice covered the lowlands during multiple glaciations. However, this was not the case everywhere. For example, in
Romania and Turkey, only Late Pleistocene glaciations have been found (Chapters 24 and 30). Mountains often display contrasting geochronologies between areas and sometimes even within the same mountain range (Hughes and Woodward, 2008). This former situation is likely to reflect regional differences in moisture supply, whilst the latter situation, whereby different geochronologies are presented for the same mountain area, are more likely to reflect problems with the reliability or interpretation of dating techniques or results—as has been discussed in this book for the Pyrenees (Chapter 11).

As in parts of Europe, the maximum ice advance of the last glaciation occurred in MIS 4 (and in some places through to MIS 3) in the mid-latitude mountains of Japan (Chapter 72) (Fig. 1.5) and Taiwan (Chapter 71). However, at mid-latitudes in the southern hemisphere, there is still debate as to whether MIS 4 was characterised by larger glaciation than MIS 2 (Chapter 75). Nevertheless, it is clear that global glaciations during the last glacial cycle, whether characterised by lowland ice sheets or mountain glaciers, at high-, mid- or low-latitude, were asynchronous (Fig. 1.5). The challenge now is to understand better why this was the case and to further constrain the timings and extents of glaciers in the different parts of the world if the implications of these apparently different timings of glacial maxima are to be more fully appreciated.
1.3.6. Stratigraphical Terminology

During the editing of this book, a proliferation of stratigraphical terms became apparent (some formal, many not) many of which were used to describe glaciations and their associated deposits. Many workers have devised quasi-stratigraphical terms that are not comparable with formally established chronostratigraphical units. This is perpetuated by the use of previously published terminologies that have no formal stratigraphical meaning, yet which are used as if they were equal in status to formally defined units such as the Würmian, Wisconsinan, etc. This was especially the case for glacial events recognised during the last glacial cycle and, as described above, the use of the term and acronym Last Glacial Maximum (LGM) is often very loosely applied (as noted above). Authors also often interchange between climatostratigraphical and chronostratigraphical terms, especially for Stadials and Chrons, and Glaciations and Stages. Future development of glacial records should endeavour to develop mutually consistent terminologies, preferably with formal stratigraphical meaning, in order to aid correct correlation and efficient communication.

As previously noted (Ehlers and Gibbard, 2007; Thackray et al., 2008), the term LGM is widely accepted as referring to the maximum global ice volume during the last glacial cycle corresponding with the trough in the marine isotope record at ca. $18^{14}$C ka BP (Martinson et al., 1987) and the associated global eustatic sea level low also dated to $18^{14}$C ka BP (Yokoyama et al., 2000). It was first applied by the CLIMAP group (CLIMAP, 1981) who adopted the date of $18^{14}$C ka BP based on the implicit assumption that globally a glacial maximum could be recognised from deep-sea sediment sequences which they used as a time-marker for the reconstruction of global climate at that time—effectively to use the maximum glacial conditions, to contrast with those of today’s interglacial situation.

The boundaries of MIS 2 have been calculated by Martinson et al. (1987) to ca. 24 ka for the base and ca. 12 ka cal. BP for the base of MIS 1 (the top of the preceding stage). It is important to realise that these boundaries are not necessarily based on natural events but on graphical plots arising from extrapolation from albeit closely spaced samples. In principle, in ocean-sediment cores, stage boundaries are placed at mid-points between temperature maxima and minima. The boundary points thus defined in ocean sequences are assumed to be globally isochronous. This is reasonable because of the extremely slow sedimentation rate of ocean-floor deposits and the relatively rapid mixing rate of oceanic waters.

However, the whole period of MIS 2 is not necessarily equivalent to the maximum development of glaciation, the LGM being effectively a point in time in the stage rather than a period. This problem has been recognised by others, although many authors who use the term LGM in chronological sense appear unaware that it has not been originally formally defined, apart from in a very general sense. Moreover, many appear to consider that the term should be taken to mean the point at which glaciation all over the world reached its maximum extent. Yet this is not the correct assumption. Since the LGM marks a trough or point in the isotope curves, it is not measuring ice extent but ice volume. Until recently, it was reasonable to assume that the two were one and the same, although evidence was always available to suggest that was an oversimplification. As evidence has accumulated from around the world, particularly through these compilations, it has become apparent that the isotope signal is not reflecting the maximum extent of glaciation worldwide but predominantly the signal from eastern North America’s Laurentide Ice Sheet. Even this signal appears to represent only the southern side of the ice sheet, whilst the north achieved its maximum extent later.

In this context, Clarke et al. (2009) have argued that most ice sheets around the world reached their maximum between ca. 26.5 and 19 ka, preceded by a maximum extent of smaller mountain glaciers between ca. 33 and 26.5 ka. This conclusion was reached based on analysis of an extensive data set covering the period 50–10 ka. However, by limiting their study to the period between 10 and 50 ka, Clarke et al. (2009) did not consider the possibility that, in many parts of the world, the maximum extent of glaciers was reached earlier in the glacial cycle. For example, in this volume, Owen notes that glaciation throughout the Himalaya was probably most extensive during the early part of the last glacial cycle and also likely during MIS 3 (Fig. 1.5). Examples of a similar situation are reported elsewhere in this book such as in the Verkhoyansk Mountains, Russia (Chapter 64), Japan (Chapter 72), Australia (Chapter 74), Arctic Russia (Chapter 28) and in some parts of the Pyrenees (Chapter 11) (Fig. 1.5). There is also limited evidence of early glaciation during the last glacial cycle in Morocco, although more dates are needed from this area (Chapter 76).

In Arctic Russia, Möller et al. (Chapter 28) note that the most extensive glaciation dates from the Early Weichselian, cumulate at ca. 100 ka, and a Middle Weichselian event of intermediate extent dates from 70 to 60 ka. The last and least extensive glaciation in Arctic Russia is contemporaneous with the so-called LGM. Even in Alaska, just west of the huge Laurentide ice sheet, the largest glaciers of the last glacial cycle formed during the early Wisconsinan and were significantly larger than late Wisconsinan glaciers (Chapter 33). In many other regions, the timing of the largest phases of glaciation during the last glacial cycle occurred later, but still well before the global LGM represented in the marine isotope record. For example, in Australia, the outermost moraines of the Snowy Mountains represent an ice advance at ca. 59 ka during MIS 4 (Chapter 74). There is no doubt that in some areas glaciers did reach
their maximum during the last glacial cycle close in time to the record of maximum global ice volume indicated in the marine isotope record. However, as becomes clear from this book, as more and more dated sequences are presented, it appears that in large parts of the world the classical LGM was a period of ice recession or with major ice maxima occurring either before or after the point itself. In this sense, it could be argued that the continued use of the term LGM is becoming a hindrance, rather than a practical ‘shorthand term’ for referring to the maximum of the last glaciation.

However, there are two points to consider. As already noted, the LGM has been taken to mean the maximum extent of glacial ice globally and has been used not only by glacial geologists across the world but also by many others who have taken it to be a time-marker for subdivision of the late Weichselian and its equivalents. The desire for fine-scale time divisions for the latter half of the last glacial period is strong. Witness the development of the event-timescale from the Greenland ice-core sequence (Björck et al., 1998). However, as also noted above, the LGM is not a time division, although it has been used as such in a quasi-chronostratigraphical sense by many workers.

Some practitioners, especially those who attempt to correlate marine and terrestrial successions, have recognised this problem. Some have even attempted to assign chronozone status. The most useful discussion of this point was made by Mix et al. (2001) who considered the event should be centred on the calibrated date at 21 ka cal. BP and should span the period 23–19 or 24–18 cal. ka BP dependent on the dating applied (e.g. MARGO project members, 2009). This useful proposal seems to have been taken up by some workers whereas others have simply ignored the problem. The problem itself is that the present concept of an event centred on a dated point infringes the rules of stratigraphical nomenclature. The question is whether the LGM represents an event (an event stratigraphical unit), which can have boundaries that vary through time, comparable to the system proposed by Björck et al. for the NGRIP sequence, or whether it is a time interval (a chronostratigraphical unit), in which case the boundaries must be fixed in time and moreover, the unit must be defined in a rock or sediment sequence. As used at present, the term LGM fulfils neither criterion. Its usefulness for communication is therefore questionable.

Until the LGM and similar divisions (e.g. ‘the mystery interval’: Denton et al., 1999; Broecker and Barker, 2007) are formally defined as chronozones, or as chronos if based on dating (geochronology), the meaning of the terms is in danger of becoming increasingly blurred; a matter that could hinder rather than help the establishment of formal divisions of Weichselian time and simplify communication. Formalisation requires acceptance and ratification by the International Commission on Stratigraphy, and at the time of writing, the Subcommission on Quaternary Stratigraphy is in the process of establishing a working group to consider the whole problem of these fine-scale time divisions.

1.3.7. Developments in Geochronology

Some of the biggest advances made in the work presented in this book have resulted from developments in geochronological understanding. In the first edition, only a few areas of the world had well-constrained glacial geochronologies. However, in this second edition, a majority of the chapter contributions present new dating evidence derived from the application of a range of new or established techniques. For some regions, this is the first time glacial geochronological data have been published (e.g. Chapter 76), whilst for many other areas, authors add to an ever-growing dataset. Future advancement in glacial research is likely to be constrained by availability of dating techniques for researchers in different countries, theoretical advancements in the dating techniques themselves and also the application and testing of multiple dating techniques to the same glacial successions. Most ages in this book are presented following the guidelines outlined in Quaternary Science Reviews (Rose, 2007) and Quaternary Geochronology (Gru¨n, 2008).

1.4. SUMMARY

The Quaternary is synonymous with extensive glaciation of the Earth’s mid- and high latitudes. Although there were local precursors, significant glaciation began in the Oligocene in eastern Antarctica. It was followed by glaciation in mountain areas through the Miocene (in Alaska, Greenland, Iceland and Patagonia), later in the Pliocene (e.g. in the Alps, the Bolivian Andes and possibly in Tasmania) and in the earliest Pleistocene (New Zealand, Iceland and Greenland). Today, evidence from both the land and the ocean floors demonstrates that the major continental glaciations, outside the polar regions, rather than occurring throughout the 2.6 Ma of the Quaternary, were markedly restricted to the last 1 Ma—800 ka or less. MIS 22 (ca. 870–880 ka) included the first of the ‘major’ worldwide events with substantial ice volumes that typify the later Pleistocene glaciations (i.e. MIS 16, 12, 10, 6, 4–2).

The growing evidence for the asynchrony of glacial maxima across the world during the last glacial cycle (i.e. the Weichselian, Würmian, Wisconsinan Stage, MIS 5d–early 1) emphasises the need to re-evaluate the concept of an ‘LGM’ representing a single global event when glaciers reached their maximum extent. Indeed, it appears that glaciations on a global scale were considerably more complex in terms of the timing and extent than previously appreciated. Apart from the obvious implications, this holds for climate and oceanic circulation reconstruction in the past, also implicit in this emerging pattern is that earlier glaciations could well have seen asynchronous maximal extents.
One possible consequence of this could be why some glaciations are represented in one region of the world, whilst in others, there is little or no record of their occurrence. In particular, this could explain why the glaciations in periods like MIS 8, 10, 14 or 18 are apparently absent from regions such as north-western Europe, when others (e.g. MIS 6, 12) are strongly represented. In the absence of a sufficiently fine-resolution geochronology, it might be difficult to examine or differentiate, but it is certain that earlier glaciations were unlikely to have been any less subject to the variable interactions of the controlling variables than the last glacial period. Nevertheless, the mutual timing of advances and retreats could potentially vary to a greater or lesser extent. The consequences could go some way to explaining the variability in extent, ice volume and chronology of glaciation during the Quaternary and earlier.

REFERENCES


