CHAPTER 1

The Quaternary record

1.1 Introduction

The Quaternary is the most recent major subdivision (period) of the geological record, and it extends up to, and includes, the present day (Figure 1.1). Together with the Tertiary it forms the Cenozoic, the fourth of the great geological eras. In the geological timescale, periods are conventionally divided into epochs, and the Quaternary includes two formally designated intervals of epoch status (Hedberg, 1976): the Pleistocene (originally meaning ‘most recent’), which ended around 10 ka BP, and the Holocene (‘wholly recent’), which is the present warm interval within which we live. However, since there is now a considerable body of evidence to suggest that the current temperate period is simply the latest of a number of warm episodes forming part of a long-term climatic cycle (see below), the last 10 ka can be seen as part of the Pleistocene epoch (West, 1977), and the Pleistocene can therefore be regarded as extending up to the present day. This interpretation is adopted here, and throughout this book the terms ‘Quaternary’ and ‘Pleistocene’ are used interchangeably, since they refer to the same interval of geological time.

1.2 The character of the Quaternary

The Quaternary has long been considered to be synonymous with the ‘Ice Age’, a view that can be traced back to the writing of Sir Edward Forbes who, in 1846, equated the Pleistocene with the ‘Glacial Epoch’. One of the most distinctive features of the Quaternary has certainly been periodic glacier activity during cold periods, with the build-up of major continental ice sheets and the expansion of mountain glaciers in many parts of the world. However, these cold or glacial stages were interspersed with warm episodes (interglacials) during which temperatures in the mid- and high latitude regions were occasionally higher than those of the present day. During the last interglacial in Britain around 120 ka BP, for example, contemporary tropical creatures such as hippopotamus swam in the River Thames, while lions and elephants roamed the present site of Trafalgar Square in central London! What makes the Quaternary distinctive, however, is not simply the occurrence of repeated warm or cold episodes, for fluctuations in global climate are apparent throughout the Cenozoic (Raymo & Ruddiman, 1992). Rather it is a combination of the high amplitude and frequency of climatic oscillations, coupled with the intensity of the colder periods in particular, that gives the Quaternary its distinctive character. In some parts of the world, temperatures may have fluctuated through more than 15°C between warm and cold episodes, temperature change was frequently rapid, and the last 800 ka alone have witnessed as many as ten full glacial/interglacial cycles. The precise number of Quaternary climatic cycles remains to be established, but evidence from the deep-ocean sediment record (see below) suggests that over the course of the full range of Quaternary time, the world may have experienced as many as fifty cold or glacial stages and a corresponding number of temperate or interglacial periods (Shackleton et al., 1990).

The effects of these climatic changes were dramatic. In the mid- and high latitudes, ice sheets and valley glaciers advanced and retreated, and the areas affected by periglacial (cold climate) processes expanded and contracted. In low latitude regions, the desert and savannah margins shifted through several degrees of latitude as phases of aridity alternated with episodes of higher precipitation. Throughout the world, weathering rates and pedogenic processes varied with changes in temperature and precipitation, river regimes fluctuated markedly, sea levels rose and fell over a vertical range of c. 150 m, and plant and animal populations were forced to migrate and adapt in response to these environmental changes.
The repeated climatic changes that have occurred throughout this latest chapter of earth history have given rise to a rich, but highly complex, record of landforms, sediments, biological (including human) remains and assemblages of human artefacts. From this legacy, it is possible to reconstruct, often with great clarity and in considerable detail, the environmental conditions and associated palaeogeography of particular intervals of Quaternary time. There are a number of separate stages in this process of palaeoenvironmental reconstruction: first, the establishment of the stratigraphy at each site in order to develop a geological framework for the investigation; second, the analysis of proxy records from those stratigraphic sequences to produce the basic palaeoenvironmental information; third, the establishment of a chronology of events which involves the development of a dating framework; fourth the linking of individual sequences from different locations by means of correlation; and finally the integration of different lines of evidence to produce an overall palaeoenvironmental synthesis. Each one of these stages contains its own set of problems. The terrestrial stratigraphic record is often highly fragmented; evidence is absent from many areas, while detailed sequences are only locally preserved. Moreover, the cyclical nature of climatic change has produced similar environmental conditions at different times and, because many records cannot be dated precisely, the process of correlation is frequently beset with difficulties. In a single exposure of Quaternary sediments, therefore, there may be much to perplex the geologist, the geomorphologist, the botanist, the zoologist or the archaeologist, and an explanation of observed geological changes will often require the combined expertise of all of these disciplines. The purpose of this book is to illustrate the very wide range of methods that are currently employed in Quaternary research, and to demonstrate that both a multidisciplinary and an interdisciplinary approach are required if a proper understanding of the complexities of the Quaternary environment is to be achieved.

1.3 The duration of the Quaternary

The beginning of the Quaternary is very difficult to establish. A view that long held sway was that the Quaternary lasted for approximately one million years (a figure derived from crude extrapolations based on weathering profiles), and that it could be differentiated from the preceding Tertiary on the basis of evidence for widespread glaciation. It is now apparent, however, that many areas of the high latitude regions supported glaciers long before the onset of the Quaternary. There is evidence, for example, of repeated glaciations during the Late Tertiary in Alaska (Hamilton 1986) and Greenland (Larsen et al., 1994), while in Antarctica the Cenozoic glacial record can be traced back to at least 38 Ma BP (Webb & Harwood, 1991). These data reflect the fact that although global temperatures had oscillated, there was a gradual worldwide cooling throughout the Tertiary period (Williams et al., 1993a). In the geological
column, therefore, the Pliocene–Pleistocene boundary cannot be drawn simply on the basis of direct terrestrial glacial evidence. Instead, the boundary has usually been located at that point in the stratigraphic record where there are the first indications of climatic cooling, reflected either in the fossil evidence or in some other climatic proxy. In Britain, for example, the Pliocene–Pleistocene boundary in the early East Anglian sequence has traditionally been placed at the stratigraphic discontinuity between the Coralline and Red Crag deposits, a horizon which coincides with an increase in abundance of marine molluscs characteristic of northern seas, and with the first appearance of elephant and horse in the vertebrate fauna (Jones & Keen, 1993). In both the British Isles and elsewhere, however, different indicators of climatic change (including various types of fossil) have been employed in different areas, and because precise dating is seldom possible, general agreement on both the position and age of the stratigraphic boundary between the Pliocene and the Pleistocene has been difficult to achieve.

The type or reference section for the Pliocene–Pleistocene boundary is located at Vrica in southern Italy. There the boundary has been placed at the first appearance of the cold-water marine ostracod Cytheropteron testudo, and dated on the basis of palaeomagnetic evidence to c. 1.64 Ma BP (Aguirre & Pasini, 1985; Harland et al., 1990). This date, which is close to the end of the Olduvai geomagnetic event (Figure 5.26), has been accepted as the geochronometric boundary for the beginning of the Pleistocene in North America (Richmond & Fullerton, 1986a), and in deep-ocean cores from the North Atlantic (Ruddiman et al., 1986). A major environmental change around the end of the Olduvai event has also been recorded in lake records from the western USA, South America and Israel, and in loess sequences from China (Adam et al., 1989; Kukla & An, 1989). Recent revision of the palaeomagnetic timescale based on ocean core evidence, however, suggests an older age for the Olduvai event (section 5.5.1.2), and hence a date for the Pliocene–Pleistocene boundary of 1.81 Ma BP (Hilgen, 1991). This age has been proposed for the base of the Pleistocene in southeast England (Funnell, 1995), while in a revised composite record from different ocean locations the Pliocene–Pleistocene boundary has been placed at c. 1.88 Ma (Williams et al., 1988).

Other interpretations suggest a much earlier date for the onset of the Quaternary. In the Netherlands, the climatic deterioration reflected in the biostratigraphic record that is considered to mark the Pliocene–Pleistocene boundary lies close to the Gauss–Matuyama boundary (Figure 5.26) on the geomagnetic timescale (de Jong, 1988). The base of the Pleistocene in the southern North Sea basin is considered to lie close to the same geomagnetic event (Long et al., 1988). This boundary is traditionally dated at c. 2.3–2.4 Ma, although a revised age estimate based on ocean core evidence places it at 2.6 Ma (Shackleton et al., 1990). A major global cooling of broadly comparable age is also reflected in other proxy data. For example, microfaunal evidence from cores from the North Atlantic and North Pacific Oceans suggest significantly colder conditions after c. 2.4–2.5 Ma BP. These are accompanied by changes in the oxygen isotope content of marine microfossils (see below and Chapter 3), and also by increased quantities of ice-rafted detritus, both lines of evidence indicative of the first major build-up of continental ice masses (Shackleton et al., 1984; Morley & Dworetzky, 1991). In China and in Central Europe, the onset of loess deposition is associated with a major environmental shift around 2.3–2.5 Ma BP (Kukla, 1987a; Kukla et al., 1990), while in lake sequences in Israel, Japan and Colombia, an environmental change of significantly greater magnitude than that at c. 1.6 Ma BP appears to have occurred around 2.4 Ma BP (Kukla, 1989).

Opinion on the duration of the Pleistocene is therefore divided between advocates of a ‘shorter’ chronology in which the Pleistocene lasted for around 1.6–1.8 Ma, and a ‘longer’ timescale of c. 2.5–2.6 Ma. Although there is perhaps a slight majority in favour of the longer chronology, it seems that there is unlikely to be a consensus view within the geological community, and that for some time yet the Pliocene–Pleistocene boundary will have to be chosen in an essentially arbitrary manner (e.g. Kukla, 1989; Williams et al., 1993a). What is apparent, however, is that the Quaternary spans considerably more time than the one million years that is still frequently quoted, although even then it covers no more than about 0.04 per cent of the total age of the earth, or approximately 0.3 per cent of the Phanerozoic, the period of geological time during which fossils have been found in rocks.

1.4 The development of Quaternary studies

1.4.1 Historical developments

The term ‘Quaternary’ can be traced back to the work of the French geologist Desmoyners who, writing in 1829, differentiated between the strata of ‘Tertiary’ and ‘Quaternary’ age in the rocks of the Paris basin. The Quaternary was redefined by Reiboul in 1833 to include all strata characterised by the remains of flora and fauna whose counterparts could still be observed in the living world. The term ‘Pleistocene’ (most recent) was first used by Lyell some six years later to refer to all rocks and sediments in
which over 70 per cent of the fossil molluscs could be recognised as living species. Only after the writings of Forbes in the 1840s did the term ‘Pleistocene’ become synonymous with the glacial period.

Quaternary studies represent one of the youngest branches of the geological sciences, with a history that goes back less than 200 years (Chorley et al., 1964; Davies, 1968). Prior to that it was generally believed that the earth had been created in 4004 BC, a figure based on genealogical calculations from biblical sources by Archbishop Ussher of Armagh and first published in 1658. Hence, early views on geological and environmental changes were constrained by the Ussher timescale of around 6000 years. As a consequence, a Catastrophist philosophy held sway in which the form and character of the earth’s surface were explained largely through the operation of great floods and other cataclysmic events. Around the turn of the eighteenth century, however, the work of the famous Edinburgh geologists James Hutton and John Playfair began to indicate that the features of the earth’s surface could more reasonably be explained by the operation, over a protracted timescale, of processes similar to those of the present day. This significant departure in geological thinking gave rise to the principle of Uniformitarianism, first expounded by Hutton, but subsequently popularised by Charles Lyell in his famous dictum ‘the present is the key to the past’. Uniformitarian reasoning, in which present-day analogues are used as a basis for the interpretation of observed features within the stratigraphic record, is still fundamental to many aspects of palaeoenvironmental reconstruction (Bell & Walker, 1992).

The nineteenth century saw a number of significant advances in Quaternary studies, many of which stemmed directly from the introduction and gradual acceptance of the Glacial Theory. Although for many years there had been speculation that certain Swiss and Norwegian glaciers had formerly been more extensive, it was not until the 1820s that credence was given to the notion of a glacial epoch. The work of Esmark in Norway (Andersen, 1992), of Bernhardi in Germany, and particularly the investigations of the two engineers de Venetz and Charpentier in Switzerland, produced evidence for former glacier activity far beyond the limits of present-day glaciers. However, it fell to the Swiss zoologist Louis Agassiz to expound, in 1837, the first coherent theory of ‘the great ice period’ involving worldwide climatic changes. Subsequently, Agassiz visited both Britain and North America and in both areas demonstrated that surficial deposits that had previously been interpreted as the products of marine inundation during the flood (diuvium) could more reasonably be regarded as the results of extensive glaciation in the relatively recent past.

Although the Glacial Theory did not immediately gain widespread acceptance, its adherents rapidly refined and developed the concept. By the 1850s evidence was beginning to emerge for two glaciations in parts of Britain and Europe and, as early as 1877, James Geikie was describing evidence for four separate glaciations in East Anglia. The strata between the glacial deposits (drift) were referred to as ‘interglacial’, and hence the idea of oscillating warm (interglacial) and cold (glacial) episodes emerged. By the end of the nineteenth century, drift sheets of four separate glaciations, the Nebraskan, Kansan, Illinoian and Wisconsinan, along with deposits of three intervening interglacials (in descending order of age, the Aftonian, Yarmouthian and Sangamon) had been identified in North America, while evidence began to emerge for multiple glaciations in different parts of Europe. Probably the most influential work in this respect, however, was that of Penck and Brückner (1909) who resolved the river terrace sequences in the valleys of the northern Alps into four separate series, each relating to a glacial episode. The phases of glaciation were named (from oldest to youngest) Günz, Mindel, Riss and Würm, after major rivers of southern Germany. In both Europe and North America, the maximum limits of Quaternary glaciations were first mapped around the turn of the twentieth century and have subsequently been modified only in detail (Figures 1.2 and 1.3), although views on the terminology adopted and on the number of glacial/interglacial stages experienced during the Quaternary have changed dramatically (see below).

Other effects of glacier expansion and contraction were also recognised at a relatively early stage. The relationship between glaciers and sea level was first considered in a systematic manner by MacLaren who, in 1841, reasoned that at times of glacier build-up sea levels would fall as water was extracted from the ocean basins and locked up in the expanding ice sheets whereas, following ice melting, sea levels would rise as water was returned to the oceans. This was the first statement of the Glacio-Eustatic Theory of sea-level change (section 2.5.2). MacLaren suggested that sea levels would fall by 350–400 ft (c. 110–130 m) during a glacial phase, a figure that is in remarkably close agreement with more recent estimates. In addition to its effects on global sea levels, the results of the build-up of ice on the earth’s surface were also noted. A number of authorities, including Playfair and Lyell, had described the raised shoreline sequences in Scandinavia and around the coasts of Scotland, and had inferred that in both regions crustal uplift had occurred. The mechanism involved in crustal warping, however, remained unclear. In 1865, the Scottish geologist Jamieson finally made the link between the raised shoreline evidence and the Glacial Theory when he deduced that crustal depression would result from the weight of the ice sheets and that uplift would follow deglaciation as the crust was free to rebound to its pre-glacial state. This was the first
vidence was of Britain Geikie was ions in East (drift) were of oscillating 12.5-25 m, emerging. Sets of four Illinoian and intervening Aftonian, tied in North for multiple bly the most hat of Penck river terraces ps into four 2. The phases nest Günz, of southern he maximum upper around frequently been though views number of during the ow), traction were: relationship widened in a reasoned that fall as water sed up in the melting, sea oceans. This ic Theory of suggested that 0 m) during a se agreement its effects on of ice on the of authorities, d the raised l the coasts of crustal uplift stal warping, tish geologist ised shoreline deduced that ght of the ice on as the crust s was the first

clear statement of what are now referred to as glacio-

isostatic effects (section 2.5.3). During the later years of the nineteenth century, evidence began to emerge for major environmental changes in areas beyond those directly affected by glacier ice. In the semi-arid southwest of the United States, for example, work by Russell and Gilbert in particular showed that extensive lakes had existed at some time in the past (Figure 1.3) and that phases of higher rainfall (pluvials) had alternated with more arid (interpluvial) episodes. Moreover, a relationship was postulated (although not clearly articulated) between these climatic oscillations and the glacial and interglacials at higher latitudes. Similar relict drainage features in desert and savannah regions in other parts of the world were described by Victorian explorers and provided further indications of climatic changes in the low latitudes. In the mid-latitude zones, on the other hand, it was gradually

recognised that phases of glacier expansion would, in turn, be accompanied by an extension of the tundra belt in which cold-climate (albeit non-glacial) processes would predominate. The term periglacial was first used to describe such regions by the Polish geomorphologist, von Lozinski, in 1909.

Biological evidence for Quaternary environmental change also began to emerge soon after the introduction of the Glacial Theory. The writings of Forbes (1846), in which various geographical components of the British flora and fauna were related to successive migrations into the British Isles under different climatic conditions, and of Heer (1865), wherein ecological changes in Switzerland were discussed in the context of Quaternary climatic changes, were particularly important milestones. In the later years of the nineteenth century, the work of the Scandinavian botanists Blytt and Sernander demonstrated the wealth of information

Figure 1.2 The maximum extent of Quaternary glaciation in Europe (modified after West, 1977).
on climatic and vegetational change that could be derived from the stratigraphy and macrofossil content of peat bogs. The scheme of postglacial climatic changes constructed by Blytt and Sernander from Scandinavian peat bog records (Table 3.9) was subsequently refined by the results of pollen analysis, a technique developed in Sweden by von Post (1916) which is still one of the most widely used and successful methods in palaeoecology (Godwin, 1975; West 1977; Birks & Birks, 1980). Systematic investigations of other forms of biological evidence also began during the last century. Important contributions in vertebrate palaeontology included that of Owen (1846), who produced the first comprehensive volume on British fossil mammals and birds, and William Buckland, who not only carried out some of the earliest detailed investigations and analyses of vertebrate assemblages in cave sites (Buckland, 1822), but was also one of the first British converts to the Glacial Theory (Buckland, 1840–41). As early as 1838, James Smith (‘Smith of Jordanhill’) was using fossil shells to demonstrate that the seas around the coast of western Scotland had been much colder in the past, thereby laying the foundation for subsequent utilisation of marine Mollusca as indicators of former marine temperatures (section 4.8). The seminal works of A.S. Kennard, often in association with B.B. Woodward, in the later part of the nineteenth and early years of the twentieth century provided a similar groundwork for the analysis of
1.4.2 Recent developments

The last fifty years have seen many important developments in Quaternary studies, but five aspects in particular merit attention. The first is the methodological advances that have been made in, and the widespread application of, a range of field and laboratory techniques. Increasingly sophisticated methods of sedimentological analysis have offered new insights into the nature of Quaternary depositional environments, while the interpretation of Quaternary stratigraphy has been greatly assisted by the development of equipment for coring terrestrial, offshore and deep-ocean sequences. Analysis of both terrestrial and marine evidence has been significantly improved by the use of a range of remote sensing techniques, including airborne sensors (e.g. conventional cameras, satellite-mounted imaging systems and radar); ground-based or ship-towed sonar, radar and seismic systems; and tracer methods for the analysis of lacustrine and marine processes. Particularly rapid progress has been made in the mapping, often at very high resolution, of sea-bottom topography and marine sediment architecture through the use of sophisticated sonar and seismic devices. Palaeoeological investigations have also benefited from a range of technological advances, notably in the extraction, recording and analysis of fossil assemblages, and in the fields of both light- and electron-microscopy. These various techniques are considered in more detail in Chapters 2–4.

The second major development has been in the dating of Quaternary events. In the nineteenth century, notions of time were founded largely on estimates of rates of operation of geological and geomorphological processes. Hence, estimated rates of delta construction, cliff retreat, stream dissection, weathering rates and degree of soil development were all used to assess the duration of Quaternary episodes (Flint, 1971). The first, and for many years the only, quantitative method for estimating the passage of time was the varve chronology developed around the turn of the century by the Swedish geologist Gerard de Geer (1912). A major breakthrough came in the years following the Second World War with the discovery, by Willard Libby, of the technique of radiocarbon dating (Libby, 1955). Other radiometric methods, notably potassium/argon and uranium-series dating, were developed in the 1950s and 1960s, along with the techniques of dendrochronology (tree-ring dating) and palaeomagnetism. The 1970s and 1980s have seen the refinement of these various methods and a general increase in levels of chronological precision, particularly as a consequence of the introduction of mass spectrometry into radiometric dating (Linick \textit{et al.}, 1989). In addition, new techniques have been developed, including aminostratigraphy, electron spin resonance measurement, luminescence measurement, and the use of long-lived cosmogenic radioisotopes such as $^{36}$Cl (Aitken, 1990). The principles and applications of the wide range of dating methods now available to the Quaternary scientist are discussed in Chapter 5.

The third important development in Quaternary studies during the course of the twentieth century has been the stratigraphic investigation of sedimentary sequences on the deep-ocean floors. Indeed, it would not be overstating the case to suggest that the results of research into ocean sediments have revolutionised our view of the Quaternary (Imbrie \& Imbrie, 1979). In one sense, trying to reconstruct environmental changes from terrestrial evidence is like trying to assemble a jigsaw puzzle and then make sense of the picture when more than 90 per cent of the pieces are missing. This is because much of the evidence has been removed by sub-aerial weathering and erosional processes and, in mid- and high latitudes, by glacial erosion. In parts of the deep oceans of the world, however, sediments have been accumulating in a relatively undisturbed manner for thousands, or even millions, of years, and therefore frequently span the entire range of Quaternary time.

Although the investigation of deep-sea sediments actually began in the nineteenth century with the voyage of the British government research vessel \textit{HMS Challenger} in 1872 (Deacon, 1973), detailed work on the fossil content of core samples from the ocean floors was first undertaken by the German palaeontologist Schott in the 1930s. Prior to the Second World War, only short sediment cores (less than 1 m in length) could be raised from the sea bed. The development of a piston corer by the Swedish oceanographer Kullenberg (1955) heralded the modern phase of deep-sea research, for with the Kullenberg corer and specially equipped research ships, it became possible to take undisturbed sediment cores more than 10 m in length. The changing fossil content of these cores has provided a remarkable record of changes in ocean water temperatures and, by implication, in global atmospheric temperatures during the course of the Quaternary (section 4.11). Many fossils, however, contain other indices of environmental change, most notably variations in oxygen isotope content. Pioneered by Emiliani (1955), oxygen isotope analysis is now regarded as one of the most powerful tools in Quaternary stratigraphy and palaeoenvironmental reconstruction (section 3.10), and continuous isotopic records are now available extending back into the early Quaternary and beyond (e.g. Ruddiman \textit{et al.}, 1989; Shackleton \textit{et al.}, 1990).
A fourth major development over recent decades has been the coring of polar ice sheets and glaciers. Continuous ice-core drilling began on the Greenland ice sheet in the late 1950s, and was followed in the 1960s by the drilling of the first deep polar ice core to reach bedrock at Camp Century, Greenland (Dansgaard et al., 1969). Subsequently, long continuous cores have been recovered from other sites in Greenland, from Antarctica, and from other polar ice caps and mountain glaciers (Oeschger & Langway, 1989). The ice layers revealed in the cores represent annual increments of frozen precipitation, and contain a range of proxy indicators (oxygen isotopes, trace gases, chemical compounds, particulate matter) of past atmospheric and climatic conditions. Ice-core data not only provide a temporal framework for Late Quaternary climatic change (section 3.11), but the upper levels of the ice cores also record the effects of recent industrial activity (e.g. Stuiber et al., 1988). The most recent phase of this research has involved the drilling to bedrock of two cores near the thickest part (>3 km) of the Greenland ice sheet by the European Greenland Ice-core Project (GRIP) and the American Greenland Ice Sheet Project (GISP2). The data from the GRIP and GISP2 programmes provide startling evidence not only of the magnitude of climatic change, but also of the rapidity and frequency with which global climates appear to have oscillated (GRIP Members, 1993).

The fifth significant advance in Quaternary science, particularly during the second half of the twentieth century, has been in the development of increasingly sophisticated computer-based models which simulate a range of aspects of Quaternary environments. This type of work began in the late 1960s with the development of General Circulation Models (GCMs), numerical models that were initially designed to reconstruct patterns of atmospheric circulation during the last cold stage, and possible linkages between terrestrial and atmospheric environments (section 7.7). A range of increasingly sophisticated models has since been developed to explore, in addition to atmospheric circulation, such diverse phenomena as ice-sheet behaviour (e.g. Boulton et al., 1985), glacio-isostatic effects (e.g. Lambeck, 1991a), oceanographical changes (e.g. Broecker & Denton, 1990a), and past vegetation dynamics (e.g. Prentice & Solomon, 1991). Some of the most impressive results have been achieved, however, where scientists from a range of disciplines have collaborated to integrate data on Quaternary environmental change from a variety of different sources, and to use those data as a basis for both descriptive and predictive modelling of Quaternary environments and environmental change. Such an approach is typified by the CLIMAP (Climate/Long Range Investigation Mapping and Prediction) group (CLIMAP Project Members, 1976, 1981), and by the COHMAP (Co-operative Holocene Mapping Project) programme (COHMAP Members, 1988; Wright et al., 1993). These interdisciplinary and multidisciplinary projects are considered in more detail in sections 4.11 and 7.7.

1.5 The framework of the Quaternary

The conventional subdivision of the Quaternary is into glacial and interglacial stages, with further subdivision into stadial and interstadial episodes. Glacial stages have traditionally been regarded as protracted cold phases when the major expansions of ice sheets and glaciers took place, whereas stadials have been viewed as shorter cold episodes during which local ice advances occurred. Interglacials are usually recognised as warm intervals when temperatures at the thermal maximum were as high or even higher than those experienced during the Holocene, and which were characterised in the mid-latitudes by the development of mixed woodland. Interstadials, by contrast, are traditionally regarded as relatively short-lived periods of thermal improvement during a glacial phase, when temperatures did not reach those of the present day and, in lowland mid-latitude regions, the climax vegetation was boreal woodland.

These terms are still widely used in Quaternary science, although they clearly lack precision and, as a consequence, are often difficult to apply. Take, for example, the problem of recognising an interglacial as opposed to an interstadial episode on the basis of degree of vegetation development. In northwest Europe, both the interglacials and interstadials of the Late Quaternary were characterised by a range of vegetation types (mixed woodland, boreal woodland, open grassland) depending on latitude, altitude, duration of the warm stage, etc. In more northerly regions, the 'vegetational signature' of an interglacial might be boreal woodland; further south, this type of forest development would be more indicative of an interstadial. Hence, the palaeobotanical distinction between 'interglacial' and 'interstadial' becomes blurred by geographical province. Moreover, this terminology may even be misleading. In the British Isles, for instance, there is no direct evidence for glacier activity during the early Quaternary cold stages (Bowen et al., 1986) and, indeed, this is also the case for many other parts of the world (Dawson, 1992). It is also apparent that during the last cold stage, Southern Hemisphere ice contributed less than 3 per cent to the overall increase in global ice volume, prompting the observation that '...the growth of ice in the Quaternary was essentially a Northern Hemisphere phenomenon' (Williams et al., 1993a, p. 31). The term 'glacial' therefore may have a different connotation in the two hemispheres.
Because of these difficulties, the terms 'temperate stage' and 'cold stage' might be considered more appropriate to describe the major climatic episodes of the Quaternary. However, these terms contain their own sets of problems (defining acceptable thresholds between 'warm' and 'cold' episodes; quantifying climatic change; conflicting proxy records for former climate, etc.) and, as a consequence, are equally arbitrary. Moreover, for historical reasons, it is not always possible to avoid the traditional terminology when referring to certain named Quaternary stages. For convenience, therefore, we have opted for the lesser of the evils and have retained the terms 'glacial' and 'interglacial' but, where appropriate, have used these interchangeably with 'cold' and 'temperate' stages. This type of categorisation, based on inferred climatic characteristics, is known as climatostratigraphy, and is considered further in Chapter 6.

Attempts to subdivide the stratigraphic record from the land areas of the Northern Hemisphere into a coherent scheme of glacial and interglacial stages that has regional or inter-regional application have hitherto proved to be extremely difficult, principally because of the fragmented nature of most terrestrial sedimentary sequences. Over the past two decades, therefore, reference has increasingly been made to the relatively undisturbed sedimentary sequence in the deep ocean, and particularly to the oxygen isotope record in the marine microfossils contained within those sediments. As will be shown in Chapter 3, the oxygen isotope trace (or 'signal') obtained from these microfossils reflects the changing isotopic composition of ocean waters over time. Insofar as the marine oxygen isotope balance is largely controlled by fluctuations in volume of land ice (Shackleton & Opdyke, 1973), variations in the isotopic signal in fossils from deep-ocean sediment profiles can be read as a record of glacial/interglacial fluctuations. Working from the top of the sequence, each isotopic stage has been assigned a number, even numbers denoting 'glacial' (cold) episodes while the 'interglacial' (warmer) phases are denoted by odd numbers. One of the most impressive features of the deep-sea oxygen isotope record is that the isotopic signal is geographically consistent, and can be replicated in cores taken from different parts of the world's oceans (Figure 1.4). Hence, the marine oxygen isotope sequence provides a climatic signal of global significance.

During the last 800 ka there have been something in the order of ten interglacial and ten glacial stages (Imbrie et al., 1984), and the total number of isotopic stages formally identified in the deep-ocean record of the past 2.5 Ma now exceeds 100 (Figure 1.5). This means that over the course of the Quaternary between thirty and fifty cold/temperate cycles may have occurred (Ruddiman et al., 1989; Patience & Kroon, 1991), depending on the age assigned to the Pliocene–Pleistocene boundary (see above). Even assuming a 'shorter' timescale for the Quaternary, this is many more temperate and cold stages than have been formally recognised and named on the basis of the terrestrial evidence. Hence, the deep-sea sequence provides an independent and unique climatostratigraphic scheme against which individual terrestrial sequences can be compared, and increasingly attempts are being made to establish correlations between these two types of record (Table 1.1). This is discussed more fully in Chapter 6.

The most comprehensive system of designated glacial and interglacial episodes is that for Northern Europe and the British Isles, with less detailed formal schemes for North America and the European Alps. There is general agreement that the Flandrian of the British sequence can be equated with the Holocene of the European and North American sequences, and that the last cold stage identified in Britain (Devensian), northern Europe (Weichselian), the Alpine region of Europe (Würmian), and North America (Wisconsinan) can be considered as broad correlatives. The Ipswichian, Eemian, Riss–Würmian and Sangamon 'temperate' records from each of these regions are also believed to be essentially coeval and are assigned to the last interglacial, despite the fact that identification is often based on quite different types of proxy evidence. In Europe, a complex sequence of stadials and interstadials during the last glacial stage (Figure 7.10) is evident in stratigraphic records from areas that lay beyond the limits of the Late Weichselian ice sheet (Behre, 1989).

Throughout northern Europe there is a broad measure of agreement over the brief climatic oscillation that occurred towards the close of the last cold stage (termed the Devensian Lateglacial in Britain and the Weichselian Lateglacial in northern Europe), for this period can be more precisely dated than older parts of the sequence. However, opinions differ over the extent to which the 'Lateglacial' can be subdivided: in Britain, most scientists accept a twofold division into a Lateglacial (or Windermere) Interstadial and a Loch Lomond Stadal (Lowe & Gray, 1980), whereas a more complex sequence with two interstadial episodes, Bolling and Allerød, separated by a brief cold episode (Older Dryas) and followed by the Younger Dryas Stadal, has been recognised in records from the European mainland (Mangerud et al., 1974; Figure 1.6). In recent years, a climatic oscillation that appears to be the correlative of the Younger Dryas cold episode has been identified in eastern North America (Wright, 1989).

Prior to the last interglacial, however, the Quaternary records are much more difficult to resolve and, although inter-regional correlations have been attempted (Table 1.1), these are frequently speculative, and become increasingly so as the age of the deposits increases. In the European Alpine
area, the sequence of glacial sediments and ‘interglacial’ soils now appears to be far more complicated than the classical Alpine model, and hence the standard nomenclature of Günz, Mindel and Riss glacials can be used only in a very general sense (Kohl, 1986; Billard, 1987). Similarly in North America, the classical terms ‘Kansan’ and ‘Nebraskan’ glacial periods and ‘Yarmouthian’ and ‘Aftonian’ interglacials have been abandoned in favour of a series of stages prior to the Illinoian Glacial that are designated simply by letter (Hallberg, 1986; Richmond & Fullerton, 1986a). In Britain and northern Europe, it is now generally accepted that several of the established named stages must contain a number of separate episodes of cold or temperate character (Table 1.1). Hence, the Cromerian Stage in Britain and in the Netherlands is believed to encompass four or more warm (interglacial?) episodes (de Jong; 1988, Jones & Keen, 1993), while two or maybe three cold or glacial events may have occurred during the classical Saalian Glacial (Sibara, 1986). A further problem concerns gaps in the terrestrial stratigraphic records. Comparison between the Dutch and British Early and Middle Pleistocene sequences, for example, suggests that as much as a million years of sedimentary history may be missing from the stratigraphic record in southern England between the Beestonian and Cromerian Stages (Gibbard et al., 1991), with other major hiatuses at other times (Table 1.1). Overall, therefore, the individual stages and suggested correlations between those stages shown in Table 1.1 must be regarded...
Table 1.1 Quaternary stratigraphy of the Northern Hemisphere. The timescale (left-hand column) is based partly on "orbital tuning" of the oxygen isotope record (section 5.5.3), and partly on palaeomagnetic stratigraphy (section 5.5.1). Marine oxygen isotope stages (section 6.2.3.5) for the past c. 800 ka are shown in the second column from the left; cold (C) and temperate (T) episodes are listed in the right-hand column. Note that beyond OI Stage 21, correlations between the marine oxygen isotope sequence and the terrestrial record are uncertain, and that many of the oxygen isotope stages have yet to be identified in the terrestrial sequence. Based principally on Srbrava (1986), with additional information from Zagwijn (1985), de Jong (1988), Shackleton et al. (1990) and Gibbard et al. (1991).

<table>
<thead>
<tr>
<th>Timescale</th>
<th>Marine Oxygen Isotope Stage</th>
<th>NORTHERN EUROPE</th>
<th>BRITISH ISLES</th>
<th>EUROPEAN RUSSIA</th>
<th>NORTHERN ALPS</th>
<th>NORTH AMERICA</th>
<th>Calt.</th>
<th>Tempereate</th>
</tr>
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<tbody>
<tr>
<td>0.01</td>
<td>Holocene</td>
<td>Holocene</td>
<td>Flandrian</td>
<td>Holocene</td>
<td>Holocene</td>
<td>Holocene</td>
<td>T</td>
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<tr>
<td>2.4d</td>
<td>Weichselian</td>
<td>Weichselian</td>
<td>Devensian</td>
<td>Devensian</td>
<td>Würm</td>
<td>Wisconsinan</td>
<td>C</td>
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<tr>
<td>0.08</td>
<td>Eemian</td>
<td>Eemian</td>
<td>Ipswichian</td>
<td>Mikulino</td>
<td>Riss-Würm</td>
<td>Sangamon</td>
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<td>0.13</td>
<td>Warthe</td>
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<td>0.19</td>
<td>Saale/Drenthe</td>
<td>&quot;Wolstonian&quot;</td>
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<td></td>
<td>Penultimate Glacial</td>
<td>Late C</td>
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<td>0.25</td>
<td>Drenthe</td>
<td></td>
<td></td>
<td></td>
<td>Odintsovo</td>
<td>Illinian</td>
<td>T</td>
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<tr>
<td>0.30</td>
<td>Dormlitz [Wecken]</td>
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<td>Dneiper</td>
<td>Early C</td>
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<tr>
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<td>Feilhe [Mehlbeck]</td>
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<td>Romny</td>
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<tr>
<td>0.35</td>
<td>Holsteinell II [Moltmberg]</td>
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<td></td>
<td>Hoxnian</td>
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<td>0.43</td>
<td>Elter 1</td>
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<td>Pronya</td>
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<tr>
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<td></td>
<td>Pre-Riss</td>
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<tr>
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<td>Elter 1</td>
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<td>Pre-Illinian A</td>
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<tr>
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<td>Lichvin</td>
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<tr>
<td>0.72</td>
<td>Glacial B</td>
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<tr>
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<td>Interglacial II</td>
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<tr>
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<td>Heime [Glacial Al]</td>
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<td>Domare</td>
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<tr>
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<td>Bavelian</td>
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<tr>
<td>1.65</td>
<td>Eburonian</td>
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<tr>
<td>1.103</td>
<td>Tiglian</td>
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<tr>
<td>2.60</td>
<td>Pliocene</td>
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</table>

to encompass the Pleistocene, three cold or the classical blem concerns. Comparison Pleistocene h as a million among the between the et al., 1991), 1.1). Overall, the correlations must be regarded
as no more than a provisional approximation of the Quaternary climatostratigraphic sequence in Europe and North America.

1.6 The causes of climatic change

It is now apparent that the climatic fluctuations of the past 2 million years or so have followed a series of distinctive patterns, and hence explanations of long-term climatic change have, in recent years, tended to focus on the factors that have given rise to both the regularity and frequency of climatic fluctuations (see reviews in, e.g., Imbrie & Imbrie, 1979; Bradley, 1985; Bell & Walker, 1992; Dawson, 1992). The hypothesis that has attracted the greatest attention is undoubtedly the 'Astronomical Theory', developed by Croll a little over 100 years ago and subsequently elaborated by the Serbian geophysicist Milankovitch. The theory is based on the assumption that surface temperatures of the earth would vary in response to regular and predictable changes in the earth's orbit and axis. Due to planetary gravitational influences, the shape of the earth's orbit is known to change over a period of approximately 100 ka from almost circular to elliptical and back again (Figure 1.7A), a process referred to as the eccentricity of the orbit. In addition, the tilt of the earth's axis varies from $21^\circ39'$ to $24^\circ36'$ and back over the space of c. 41 ka (Figure 1.7B). Because the angle of tilt is measured relative to an imaginary line representing the plane of the ecliptic (the plane described by the earth's elliptical path around the sun), this phenomenon is known as the obliquity of the ecliptic. The third variable arises because the gravitational pull exerted by the sun and the moon causes the earth to wobble on its axis like a top (Figure 1.7C). The consequence of this is that the seasons (or the equinoxes) seem to move around the sun in a regular fashion, hence the term precession of the equinoxes or precession of the solstices. In effect this means that the season during which the earth is nearest to the sun (perihelion) varies. At present, the Northern Hemisphere winter occurs in perihelion (Figure 1.7C(i)) while the summer occurs at the furthest point on the orbit (aphelion). In about 10.5 ka time, the position will be reversed (Figure 1.7C(iii)), while c. 21 ka hence the cycle will be complete. In fact, it now appears that there are two separate interlocked cycles, a major one averaging around 23 ka and a minor one at c. 19 ka.

These variables, in combination, exert a profound effect on global temperatures. The total amount of radiation received is determined largely by the eccentricity of the earth's orbit, while the other astronomical variables affect the way in which that heat energy is distributed at different latitudes. In general it seems that solar radiation receipt in the low and middle latitude regions is governed mainly by precession and eccentricity variations, while in higher latitudes the effects of eccentricity are modulated or amplified by changes in obliquity. Patterns of change through time can be calculated from astronomical data (Figure 1.8A) and Milankovitch was therefore able to obtain

![Figure 1.5 Oxygen isotope profile spanning the last 2.6 Ma obtained from benthonic (deep-water) Foraminifera from Ocean Drilling Programme (ODP) Site 677. The core was raised from a water depth of 3461 m at a site in the Eastern Pacific off the coast of Ecuador (latitude 1°12'N; longitude 83°44'W). Selected oxygen isotope stages are also shown (after Shackleton et al., 1990).](image-url)
The causes of climatic change

estimates for radiation inputs at different latitudes, and hence to infer temperature changes through time.

The theory was first published in 1924 and initially found favour with many European geologists, for the sequence of warm and cold stages predicted by the radiation curves appeared to match the record of glacial and interglacial in the classical Alpine region of Penck and Brückner. Increasingly, however, it became apparent that the timing and frequency of glacial episodes during the Late Quaternary did not seem to accord with the pattern of climatic changes predicted by the astronomical variables. This was thrown into sharp relief in the 1940s and 1950s with the development of radiocarbon dating which provided, for the first time, an independent chronology for the Late Quaternary glacial sequence. By the mid 1950s, the Milankovitch hypothesis as an explanation of climatic change had been almost universally rejected. In the late 1960s and early 1970s, however, work initially on sea-level changes and subsequently on deep-sea sediments reawakened interest in the Milankovitch hypothesis (Imbrie & Imbrie, 1979). Of particular significance was the discovery of oxygen isotope variations in marine microfossils which provided a long-term proxy record of environmental and climatic change (section 3.10; Figure 1.8B). Spectral analysis of ocean core sequences revealed evidence of cycles of 100 ka, 43 ka, 24 ka and 19 ka in the isotopic signal, with the longest cycle driving the glacial/interglacial oscillations of the past 700 ka or so while the others, in combination, modulate or amplify the effects of longer-term changes (Hays et al., 1976). These data provided the first unequivocal evidence of the 100 ka eccentricity cycle, the 41 ka obliquity cycle and the 23 ka and 19 ka precessional cycles in the geological record, and were an impressive demonstration of the role of the astronomical variables in determining patterns of long-term climatic change – hence the title of the seminal paper of Hays et al. (1976), 'Variations in the earth's orbit: pacemaker of the Ice Ages'. Subsequently, evidence of the influence of the astronomical variables has been detected in a wide range of proxy records including coral reef sequences (e.g. Aharon 1984), pollen records (e.g. Hooghiemstra et al., 1993), loess sequences (e.g. Kukla, 1987b), ice cores (e.g. Lorius et al., 1990) and tropical lake records (e.g. Kutzbach & Street-Perrott, 1985). Collectively these data would seem to confirm the hypothesis that changes in the earth's orbit and axis, that have become known as orbital forcing, are the primary driving mechanism in Quaternary climatic change (Imbrie et al., 1992, 1993).

Although the Astronomical Theory offers a coherent explanation for the sequence of major Quaternary climatic oscillations, it is now apparent that other factors have also influenced the course of global climatic change. For example, although the earliest evidence for the build-up of moderate-sized continental ice sheets dates from around 2.5 Ma BP (Shackleton et al., 1984), proxy data from deep-ocean cores suggest that the climate had cooled, albeit in an oscillatory manner, from around 3.15 Ma onwards (Ruddiman & Raymo, 1988). In addition, the climatic cycles of the Quaternary have not been constant, but have shifted from a periodicity of around 41 ka prior to c. 800 Ma BP to a prevailing rhythm of c. 100 ka over the course of the last 700–800 ka (Ruddiman et al., 1986). This, in turn, was accompanied by an apparent intensification of glaciation, with the growth of Northern Hemisphere ice sheets to volumes very much larger than those attained over the course of the previous 1.6–1.7 Ma (Ruddiman & Raymo,
Figure 1.7 The components of the Astronomical Theory of climate change: A, eccentricity of the orbit; B, obliquity of the ecliptic; C, precession of the equinoxes.
This sequence of changes cannot be accounted for solely by the Milankovitch model of orbital forcing. The major additional elements in the climatic equation which serve to modulate or amplify the effects of the astronomical variables appear to be changes in the disposition of the continental landmasses, tectonic activity, feedback mechanisms caused by oceanic circulation and changes in the extent of ice cover (Broecker & Denton, 1990a, 1990b) and, possibly, variations in the constituents of the atmosphere including, for example, CO₂, methane (CH₄), and dust particles. The long-term global cooling trend referred to above has been widely attributed to the gradual migration towards the polar regions of the major continental land masses (Williams et al., 1993a). In addition, the closing of the Isthmus of Panama some 3.0–3.5 Ma ago (Keigwin, 1978) would have prompted major changes in the oceanic heat and moisture flux in the North Atlantic region, while uplift along the major mountain belts such as the Himalayas, which have risen by some 3000 m over the course of the past 2 Ma alone (Liu et al., 1986), would have led to significant cooling, especially in winter (Birchfield & Weertman, 1983). Land uplift may also have affected the wave structure of the airstreams of the upper atmosphere, the effects of which would have been to cool Northern Hemisphere landmasses, thereby making them especially susceptible to orbitally driven insolation changes. This particular hypothesis, which involves the attainment of key elevation thresholds, has been advanced to explain both the initiation of widespread glaciation in the Northern Hemisphere around 2.5 Ma BP, as well as the intensification of glacial activity during the mid-Quaternary (Raymo & Ruddiman, 1992).

In addition to these long-term variations in climate during the Quaternary, high-resolution proxy records provide evidence of rapid climatic variations, frequently of large amplitude, which are superimposed on the orbitally driven cycles. These short-lived ‘sub-Milankovitch’ events occur over timescales varying from centuries to millennia and have been found, inter alia, in ice-core records from Greenland (GRIP Members, 1993), terrestrial records of the last glacial stage from northwest Europe, and lake records from northern and eastern Africa (Street-Perrott & Roberts, 1983; Gasse et al., 1990). Energy transfer in the world’s oceans, driven by salt-density variations (‘thermohaline circulation’), along with chemical changes resulting from biological activity, are being increasingly considered as major causal factors underlying these events. For example, the abrupt climatic changes that have occurred during the Late Quaternary in many low-latitude regions may be related to subtle changes in the nature and rate of North Atlantic ocean circulation, with fluctuations in sea-surface temperatures (SSTs) influencing the pattern and timing of tropical monsoons, in turn leading to marked spatial and temporal variations in precipitation over tropical Africa (Street-Perrott & Perrott, 1990).

Data from both ocean cores and the polar ice sheets indicate that atmospheric CO₂ levels were significantly lower during the last cold stage than during either the present or last interglacials (Shackleton et al., 1983; Barnola et al., 1987), and a similar pattern has been detected in other gases, notably CH₄ (Chappellaz et al., 1990; Nisbet, 1990, 1992). The close parallels between the CO₂ and temperature profiles from Antarctic ice cores (Chapter 3) has led to the suggestion that CO₂ may also be a major forcing factor in long-term climatic change (Genthon et al.,

**Figure 1.8**

A. Variations in eccentricity, obliquity and the precessional index over the past 800 ka. The three time series have been normalised and added to form the composite curve labelled ETP. The scale for obliquity is in degrees and for ETP in standard deviation units. B. Normalised and smoothed variations in the oxygen isotope signal (δ¹⁸O) in five deep-sea cores. Note the similarity between this record and the ETP curve above (after Imbrie et al., 1984).
1987; Lorius et al., 1990), while other gases such as CH₄ might have had a similar effect. Precisely how changes in the gas composition of the atmosphere could have operated in this way remains to be established, but there is now a considerable body of data to suggest that CO₂ (and perhaps also CH₄) were important components in the system of climatic feedbacks that modulated the direct effects of insolation changes resulting from orbital forcing (Pisias & Shackleton, 1984). Possible ways in which the interaction between these various oceanic and atmospheric parameters might lead to global climate change are considered more fully in section 7.8.

1.7 The scope of this book

The aim of this book is to provide a critical assessment of the methods and approaches that are currently employed in the reconstruction of Quaternary environments. The work does not, however, claim to be exhaustive. Indeed in view of the wide range of disciplines involved in Quaternary research and, particularly, the ‘information explosion’ that has occurred over the past two decades, a comprehensive treatment would run far beyond the space of a single volume. Some aspects are, therefore, considered only briefly, while others (which some will no doubt believe to be important) are omitted altogether. To some extent the choice of material reflects the interests of the authors, but an attempt has, nevertheless, been made to present a balanced view of the various methods employed in, and sources of evidence that form the basis for, Quaternary environmental reconstructions. Some temporal bias is inevitable, as far more is known about the later part of the Quaternary than about the earlier parts of the period, and therefore the majority of examples are drawn from the last interglacial and last glacial stages. The methods, approaches and principles are, however, equally applicable to the analysis of Early and Middle Quaternary environments. In addition, although there is an emphasis on evidence from the Northern Hemisphere mid-latitude regions, particularly from Europe and North America, it is hoped that readers in other parts of the world will find material here that is of interest to them.

The book falls naturally into three parts. In Chapters 2, 3 and 4, the geomorphological, lithological and biological evidence that forms the basis for environmental reconstruction is outlined. Although these are useful general categories within which to describe particular techniques and approaches, they are, to some extent, artificial and there are considerable overlaps between them. Hence, in Chapter 2, where the emphasis is on geomorphology (i.e. surface architecture), certain aspects of the stratigraphy of river terraces and raised shoreline sequences need to be considered also, while in Chapter 3, where sedimentological evidence is being discussed, reference is frequently made to landform evidence as, for example, in the analysis of sand dunes formed in loess and coversand deposits. In all three chapters, field and laboratory techniques are introduced in order to give an indication of the procedures that are involved in generating the basic data.

Chapters 5 and 6 make up the second part of the book. The various dating methods that are currently employed in Quaternary science are described and evaluated in Chapter 5, while the principles of stratigraphy and correlation which enable the researcher to construct meaningful spatial and temporal sequences from often fragmentary evidence are outlined in Chapter 6. The final part (Chapter 7) consists of a discussion of the sequence of events in the North Atlantic region during the last climatic cycle. It illustrates how often diverse evidence can be synthesised into a coherent picture of environmental change and, in particular, the significance of the linkages between the terrestrial, atmospheric and oceanographic components of the natural environment. Insofar as it highlights the gaps in our present state of knowledge, it also serves as a starting point for the next generation of investigations of Quaternary environments.

Notes

1. Throughout this book, the shorthand form is used for years before present (BP): ka – thousand years; Ma – million years. Radiometric dates are quoted in uncalibrated form, and the present is taken as 1950 calendar years AD.

2. Because the end of the Pleistocene is designated as the end of the last cold (‘glacial’) stage, the period of time since then (the last 10 ka) is often referred to informally as the ‘Postglacial’. In Britain and in some other parts of northwest Europe, however, the term ‘Flandrian’ is used as a formal name for the present temperate (‘interglacial’) stage, in place of the informal and somewhat more equivocal term Postglacial (or the adjective ‘post-glacial’). The name Flandrian derives from the marine transgression which culminated during the present warm stage on the Flemish coastal plain, and follows European practice in naming temperate stages of the Quaternary (e.g. Eemian, Holsteinian) after their characteristic marine transgressions (Hyvärinen, 1978; West, 1979). ‘Flandrian’ has not been widely adopted outside the British Isles, however, and therefore in this book we use the internationally accepted formal chronostratigraphic term ‘Holocene’ for the time interval of the last 10 ka (see Chapter 6).

3. Nevertheless, the International Commission on Stratigraphic Nomenclature (Hedberg, 1976) recommended that, in the
geological record, the Quaternary System should be formally divided into a **Pleistocene Series** and a **Holocene Series**, and this has been endorsed in subsequent international stratigraphic codes (e.g., Whittaker et al., 1991). As a consequence, many Quaternary scientists continue to regard the Pleistocene and Holocene as separate Quaternary intervals each of epoch status.

4. The term **proxy** or **proxy record** is used to refer to any line of evidence that provides an **indirect** measure of former climates or environments. It can include materials as diverse as pollen grains, isotopic records, glacial sediments, tree rings or animal bones (Bell & Walker, 1992).

5. The term **'precession'** describes the slow movement of the axis of rotation of a spinning body (e.g., a gyroscope) about a line that makes an angle with it, so as to describe a cone (Figure 1.7C). It is caused by a torque acting on the rotation axis to change its direction, and is a motion continuously at right angles to the plane of the torque and the angular momentum vector of the spinning body.

6. An alternative explanation of the 100 ka 'glacial' cycle is that it is caused not by eccentricity, but by a previously ignored parameter: **orbital inclination**, or the **tilt of the earth's orbital plane** (Muller & MacDonald, 1995). However, although there appears to be a close correspondence between orbital inclination and the marine δ¹⁸O record, a cause and effect relationship between orbital inclination and long-term climatic change remains to be established.