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Bicentennial Review

Quaternary science 2007: a 50-year retrospective

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Abstract: This paper reviews 50 years of progress in understanding the recent history of the Earth as contained within the stratigraphical record of the Quaternary. It describes some of the major technological and methodological advances that have occurred in Quaternary geochronology; examines the impressive range of palaeoenvironmental evidence that has been assembled from terrestrial, marine and cryospheric archives; assesses the progress that has been made towards an understanding of Quaternary climatic variability; discusses the development of numerical modelling as a basis for explaining and predicting climatic and environmental change; and outlines the present status of the Quaternary in relation to the geological time scale. The review concludes with a consideration of the global Quaternary community and the challenge for the future.

In 1957 one of the most influential figures in twentieth century Quaternary science, Richard Foster Flint, published his seminal text *Glacial and Pleistocene Geology*. In the Preface to this work, he made reference to the great changes in 'our understanding of Pleistocene events that had occurred over the previous decade resulting from new, rapidly evolving methods of dating, from pollen studies, and from the stratigraphy revealed by sediment cores from beneath the oceans' (Flint 1957, p. v). Despite his implicit acknowledgement of the multi-disciplinary nature of Pleistocene–Quaternary investigations, however, Flint's approach was firmly rooted in glacial geology and, although he accepted that other approaches are possible, at the time he saw 'little reason yet to alter that basic direction' (Flint 1957). Indeed, the leitmotif of the book is the 'ice age', and in this sense Flint was essentially espousing the view, first articulated over a century before (Forbes 1846), that the Quaternary is synonymous with the 'Ice Age' or 'Glacial Epoch'.

Re-reading Flint's words in the first decade of the twenty-first century, it is striking just how much Quaternary science has changed. Apart from the considerable technical developments in field techniques, in laboratory methods and in computing, all of which have revolutionized Quaternary studies, a hallmark of Quaternary research in recent decades has been the increasing collaboration between scientists from diverse disciplines. This has moved Quaternary investigations away from Flint's somewhat narrow glacial-geological paradigm towards the multi- and inter-disciplinary approach to the study of recent Earth history that is practiced today. In addition, the opening up of new geological archives in deep lakes, on the ocean floors and in the polar ice sheets has provided new insights into Quaternary environmental change. Concomitant advances in geochronology have equipped Quaternary scientists with an array of dating tools, and a time-stratigraphic framework for reconstructing past changes of remarkable accuracy and precision. These and other methodological developments allow the rich and often readily accessible Quaternary record to be analysed at a level of detail not normally possible for older geological periods, and provide the best available 'laboratory' for researching Earth-system processes. Moreover, although unlocking the Quaternary geological record rests firmly on the use of modern analogues, the uniformitarian approach can be inverted so that 'the past can provide the key to the future'. In this way, therefore, evidence from the Quaternary stratigraphic record provides key baseline data for predictions of future climate change (Rind 1999; Houghton *et al*. 2001) and its effects (e.g. Cowling *et al*. 2004).

Quaternary geochronology

Recent advances in Quaternary geochronology have produced a portfolio of dating tools that could scarcely have been envisaged 50 years ago (Walker 2005). Indeed, in his 1957 book, Flint makes reference only to geomorphological processes (weathering rates, etc.), 'rhythmic natural processes' (dendrochronology and rhythmites or varves), and radioactive isotopes as potential bases for dating, the last category being dominated by the then recently developed technique of radiocarbon dating. He was also unable to place an age on the beginning of the Quaternary, noting that 'the Pleistocene as a whole embraces a span of at least 300,000 yr, and perhaps much more' (Flint 1957, p. 301). Subsequently, however, a suite of radiometric and other dating methods has emerged that not only allows the duration of the Quaternary to be determined, but that frequently permits events to be dated with a millennial precision, although decadal to annual resolution is possible in certain contexts.

Radiometric dating

Some of the most significant technical and methodological innovations over the last few decades have been in radiocarbon dating. The technique was revolutionized in the 1980s by accelerator mass spectrometry (AMS), which allows dates to be obtained from milligram-scale samples. Advances in AMS target preparation have also extended the conventional range of radiocarbon (*c*. 45 ka) to finite ages in excess of 50 ka (Bird *et al*.

2003). In addition, innovations in sample pretreatment and purification mean that more accurate ages can be obtained on complex materials, such as bone and sediment (Jacobi *et al*. 2006). The discrepancy between radiocarbon and calendrical age, resulting from variations in atmospheric ^{14}C concentration, has now largely been resolved by the construction of calibration curves based on comparisons between radiocarbon-dated samples and chronologies obtained from independent dating of annually banded records, principally tree rings (dendrochronology), but also varved sediments and carbonate materials, such as speleothems or corals (Balter 2006, and see below). The calibration curve adopted by the international radiocarbon community is INTCAL, the most recent version of which (INTCAL04) extends back to 26 ka BP (Reimer *et al*. 2004).

The introduction of AMS also paved the way for the most recently developed of the radiometric techniques, cosmogenic nuclide dating (CN dating). It had long been known that radionuclides generated by interaction between cosmic rays and rock minerals at the Earth's surface could have geological applications, but it was not until the development of AMS that low natural levels of cosmogenic nuclides (such as ^{10}Be, ^{26}Al, ^{36}Cl) could be measured (Gosse & Phillips 2001). The applications of CN dating, which has a potential age range from the Pliocene to the late Holocene, include the determination of exposure ages of rocks and rock surfaces in deglaciated terrain, the dating of sediment burial, and the measurement of rates of operation of geomorphological processes and long-term landscape evolution (Cockburn & Summerfield 2004). The technique has been particularly widely used in the development of glacial chronologies in mountain regions on time scales of a few thousand years to, in some cases, more than 100 ka (e.g. Farber *et al*. 2005; Owen *et al*. 2006).

There have also been important technological developments in uranium-series dating, with alpha spectrometry (indirect measurement of uranium concentrations based on decay pathways) being largely replaced by mass spectrometric analysis using thermal ionization mass spectrometry (TIMS). More recent innovations include multi-collector inductively coupled plasma mass spectrometry (ICP-MS) and laser-ablation (LA)-ICP-MS (Goldstein & Stirling 2003; Eggins *et al*. 2005), instrumentation that has led to improvements in sensitivity, speed and analytical precision, as well as a widening of scope of the method to include materials of very low uranium isotope concentration. The U-series technique is applicable to a range of carbonate materials, including speleothem, coral, mollusc shell and bone (Ivanovich & Harmon 1995), while soil or sediment concretions and nodules, as well as secondary carbonate cements (e.g. in glacial deposits), can also provide suitable material for dating (Parfitt *et al*. 2005; Hughes *et al*. 2006). The technique is effective over time ranges from a few hundred years to *c*. 350 ka using alpha spectrometry, and from around 50–100 years to *c*. 500 ka by mass spectrometry.

Some of the most important advances in Quaternary radiometric geochronology over the past few decades have been in luminescence dating (Lian & Roberts 2006). It had long been known that electrons that accumulated through low-level radiation in mineral crystal lattices of fired materials (pottery, brick and tile) could be released by reheating, the intensity of the resulting glow curve (thermoluminesence; TL) being proportional to the number of electrons trapped, reflecting the lapse of time since the initial firing. In the 1970s, this approach was first applied to sediments, working on the principle that the luminescence signal from minerals in sedimentary sequences would reflect the time interval since removal from sunlight; in other words, it would provide a date for burial (Wintle & Huntley 1980). A key development was the discovery that electrons could be stimulated by visible light and that optically stimulated luminescence (OSL) could date deposition of quartz- and feldspar-rich sediments (Huntley *et al*. 1985). Recent innovations in OSL include the employment of IR stimulated luminescence (IRSL) to feldspar grains to generate a stronger luminescence signal, the application of the single aliquot regeneration (SAR) method, which uses repeated measurements on a single sample (Lang *et al*. 1998), and the derivation of an OSL signal from a single mineral grain (Roberts *et al*. 1999). Reliable OSL ages (with relatively small errors) can now be obtained from materials as young as 200–300 years, and the upper end of the scale extends to 100–150 ka and maybe even older.

Technical advances in three other radiometric techniques have also been important for Quaternary geochronology. In the late 1960s and 1970s, a variant of the potassium–argon ($^{40}K/^{40}Ar$) method was developed, which involved the measurement of the ratios between two argon isotopes, ^{40}Ar and ^{39}Ar in volcanic rocks (McDougall & Harrison 1999). The greater levels of analytical precision associated with the $^{40}Ar/^{39}Ar$ method allowed much younger samples to be dated than with $^{40}K/^{40}Ar$, and meaningful ages as young as 2 ka have subsequently been obtained using this approach (Renne *et al*. 1997). Also in the 1970s, electron spin resonance (ESR) dating, which had been developed some 40 years earlier, was first successfully applied to Quaternary speleothem calcite (Ikeya 1975), since when it has been used to date tooth enamel, coral, molluscs, burnt flint, and quartz-bearing rocks and sediments (Rink 1997). The time range of the technique is from a few thousand years to *c*. 2 Ma, but it has been most frequently employed to date materials between 40 ka and 200 ka in age. There have also been important technical advances in fission-track dating, which employs the number of damage trails created by spontaneous fission reactions (fission tracks) in volcanic minerals such as glass (tephra) and zircon (Bernet & Garver 2005) to infer passage of time, and which can provide ages on materials ranging from a few hundred years back to the beginning of the Quaternary and beyond (van den Haute & Corte 1998).

Annually banded records

Counting annual increments of material was one of the earliest methods for determining Quaternary time, with varve chronology being employed over 100 years ago, and dendrochronology first being applied as a systematic dating technique in the 1930s. During the later years of the twentieth century, there have been important technical and methodological developments in both dating methods. Advances in coring technology and in the digital imaging of sedimentary sequences have led to the creation of high-resolution time-stratigraphic frameworks for environmental reconstructions based on varved sediment records (Lindeberg & Ringberg 1999). Comparable technical advances have also aided the counting and cross matching of tree rings, and a number of continuous dendrochronological series have now been constructed (Fig. 1). The longest of these, the combined oak and pine chronology for central Europe, currently spans the past 11 919 years and may eventually be extended back to at least 14 300 years (Friedrich *et al*. 2001). Varved records from both marine and lacustrine contexts (Hughen *et al*. 1998; Kitagawa & van der Plicht 2000), and long tree-ring series, have been key elements in the calibration of the radiocarbon time scale (see above).

Other annually banded materials that can be employed as

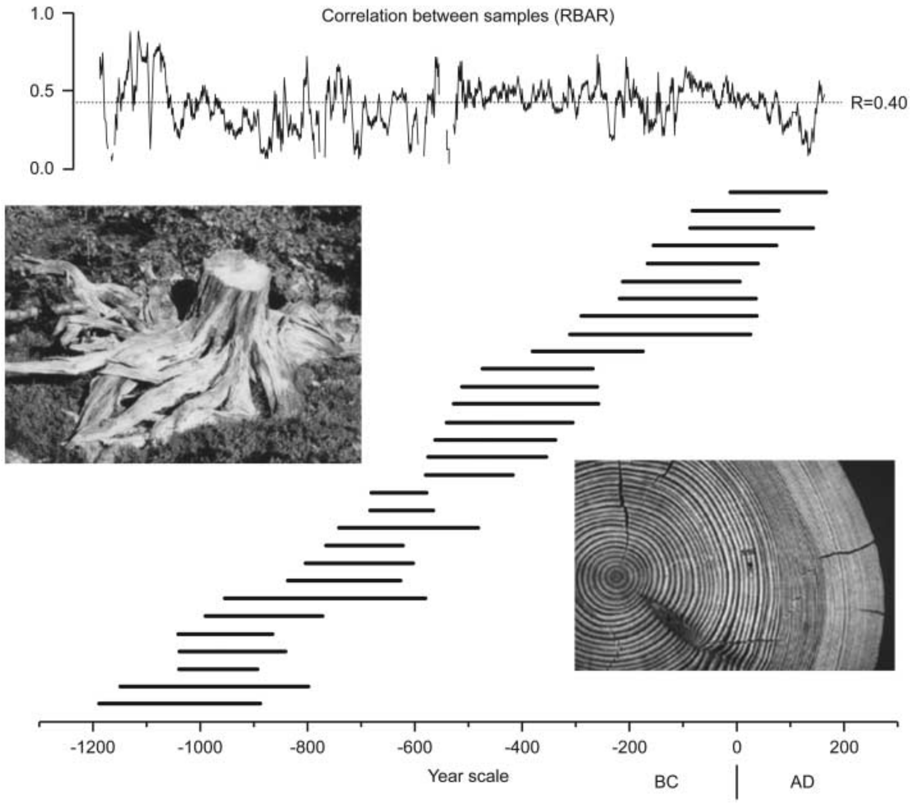

Fig. 1. A dendrochronological record from Finnish Lapland for the period ad 200 to 1200 bc (after Eronen *et al*. 2002). The black horizontal bars show the time intervals spanned by individual fossil pine tree remains. Statistical cross-matching of patterns in ring-width variation between tree rings can be extended to older fossils, and has allowed a continuous 7000 year long chronology to be constructed. Similar approaches have led to the development of even longer continuous tree-ring chronologies for the western USA and central Europe (Ferguson & Graybill 1983; Friedrich *et al*. 1999). Left inset: a sub-fossil pine stump (northern Sweden). Right inset: cross-section showing clear variations in ring-width.

chronometers are lichen thalli, mollusc shells, coral structures and carbonate precipitates (speleothems), and there have been important recent developments in the use of each of these as a basis for dating. The technique of lichenometry, which uses lichen thallus size as an index of time-lapse since surface exposure and initial lichen colonization, was first employed more than 50 years ago, since when it has been used to date a range of late Holocene events, most notably rates and patterns of deglaciation (Bickerton & Matthews 1993). Sclerochronology, which is based on annual growth bands in corals and bivalves (such as oysters), is a more recent innovation in Quaternary geochronology. In corals, the fine growth bands provide a time scale for changes in the marine environment over the past 200–300 years (Hendy *et al*. 2003) and, although bivalves are more short-lived than corals, visual cross-matching between living and dead species (as in dendrochronology), and between older fossil specimens recovered from marine cores (Scourse *et al*. 2006), aided by isotopic data on seasonal growth variations, offers a basis for much longer chronologies (Kirby *et al*. 1998; Marchitto *et al*. 2000). Recent technical developments in the analysis of speleothem carbonate have also allowed annual incremental bands to be detected (McMillan *et al*. 2005), and in ice cores, annual layers identified from a range of physical and chemical properties (‘multi-parameter counting’) also form a basis for dating (Rasmussen *et al*. 2006). In both of these cases the resulting chronologies extend over much longer time ranges.

Other dating methods

Variations in rock surface weathering or degree of soil development have long been used to provide a basis for relative glacial chronologies, but observational data on surface weathering rinds have, in recent years, been augmented by quantitative estimates of weathering (McCarroll 1994). Quantitative approaches to pedogenic studies have generated soil development indices, which can be used to establish temporal and regional trends in soil development, and calibration (e.g. by radiocarbon) allows soil chronofunctions to be constructed, which transform the relative soil development indices into a basis for dating (Birkeland 1999). Post-mortem changes in fossil material also provide a relative time scale for Quaternary events. An important development in this field has been amino-acid geochronology, which is based on diagenetic alteration of amino-acid ratios in proteinaceous residues (Goodfriend *et al*. 2000). This technique, which was developed in the 1960s and originally employed carbonaceous fossils such as molluscs and egg-shells, has more recently been applied to organic residues in cave speleothem carbonate (Lauritzen *et al*. 1994), and to organic materials incorporated into marine carbonates, where it can provide a relative chronology for sea-level change (Hearty & Kaufman 2000).

Two types of time-parallel marker horizon have proved valuable in Quaternary geochronology: palaeomagnetic signatures and tephras. The long-term sequence of dipole changes in the Earth’s magnetic field (polarity epochs, events and excursions) is now well constrained by argon isotope dating, and the palaeomagnetic time scale constitutes a unique template for Quaternary Earth history (Cande & Kent 1995). However, palaeosecular variations occurring over time scales of centuries also provide a basis for dating, particularly of Holocene limnic sequences (Ojala & Saarinen 2002). Tephrochronology was first applied in the 1920s, but it is only recently that the full potential of this technique as a basis for dating and correlation has begun to be realized (Alloway *et al*. 2007), largely as a result of technical advances in the detection, extraction and provenancing of tephra materials (Haflidason *et al*. 2000; Turney *et al*. 2004). Innovations in laboratory procedures now allow non-visible, fine volcanic ash ('microtephras' or 'cryptotephras') to be extracted from peats, lake, and marine sediments up to 3000 km from volcanic sources, greatly extending the range over which deposits can be correlated (Davies *et al*. 2002). Electron probe micro-analysis (EPMA) and a range of mass spectrometric methods mean that a precise geochemical 'fingerprint' can now be obtained for individual tephras, linking these to known volcanoes and to specific eruptions.

Biostratigraphical evidence has long been used in Quaternary science as a basis for relative dating and correlation. The palynological signature of interglacial deposits in the fragmentary European terrestrial record has been widely employed as a means of determining their chronostratigraphical position and age (Tzedakis *et al*. 2001), and well-defined palynological events, such as the *Tsuga* decline (*c*. 5.5 ka) in eastern North America and the *Ulmus* decline (*c*. 5.8 ka) in western Europe, constitute important chronostratigraphic markers in Holocene sequences (Bennett & Fuller 2002; Parker *et al*. 2002). Mammalian biostratigraphy has been increasingly used to differentiate between successive early and middle Pleistocene interglacials throughout western Europe (Turner 1995; Schreve 2001), and species-specific evolutionary changes, as in the dentition of the water vole *Arvicola* in Middle Pleistocene European sequences (the 'vole clock': Koenigswald & van Kolfschoten 1995), also form a basis for relative chronologies.

Validation of age models

One of the more remarkable discoveries in Quaternary science in recent years is that global environmental changes were more frequent and often more abrupt than was hitherto envisaged, with some climatic shifts occurring within a matter of decades (see below). There are, however, relatively few geochronological methods that can resolve such events with this degree of precision. All geological age estimates have associated statistical uncertainties and/or counting errors that limit the precision with which events can be dated, and this constitutes a difficulty for detailed studies of recent Earth history. A major trend in Quaternary science over the course of the last decade or so, therefore, has been not only increasing refinement of the analytical aspects of different dating methods, but also the rigorous testing of age models derived from radiometric or other techniques. This has involved, *inter alia*, the use of time-parallel markers (palaeomagnetic signatures, tephra horizons) as a cross-check on radiometric ages, an increase in the number of sample measurements to allow more robust statistical tests of trends in the data (e.g. Bayesian analysis), and the combination of results from different dating methods to provide a basis for cross-validation (Buck *et al*. 2003; Lowe *et al*. 2004; Fairbanks *et al*. 2005).

Quaternary archives

The Quaternary stratigraphical record is undoubtedly the richest in terms of quality of preservation and degree of resolution of any of the periods or sub-eras within the geological column. Prior to the 1950s, Quaternary history was based almost entirely on the terrestrial stratigraphic record. Since then, however, a substantial body of data has been recovered from the oceans' sediments and from ice sheets, which has transformed our knowledge of the nature of Quaternary environments, of the processes driving environmental change, and of the interactions between components of the Earth–ocean–climate system. Progress over the past five decades in the recovery, analysis and interpretation of data obtained from these three key global archives is considered in this section.

The terrestrial record

Geological evidence. The legacy of the great climatic and environmental changes that characterize the Quaternary are reflected in both Earth-surface morphology and in the near-surface rock-stratigraphic record. In the 1950s, interpretations of these records were based largely on field mapping and survey, on shallow core sequences and on a limited number of exposures, with some input from aerial photography. The principal geographical focus was on the northern mid-latitude regions, and knowledge of the Quaternary record from the tropics, sub-tropics, polar and high-altitude regions was limited. The past half-century has witnessed not only major technological and methodological advances, but also an extension in geographical coverage, to the extent that there are now few areas of the Earth's land surface where there is not a working knowledge, at least in outline, of the regional Quaternary stratigraphic record.

The most important technical developments have been in the fields of remote sensing and coring. Innovations in aerial photography, involving both visible and non-visible (IR) light spectra, allow landforms and landform assemblages to be mapped in very high levels of detail. Since the mid-1970s, conventional aerial photography has been augmented by satellite imagery, and the high-resolution digital images produced by the multi-spectral scanning systems have revolutionized Earth-surface mapping (Kramer 1994). Synthetic aperture radar (SAR) carried by aircraft or by satellites has been a further innovation in terrain mapping, and seismic sensing has also become a routine technique in the investigation of Quaternary sediments and landforms (Roberts *et al*. 1992). There have also been important developments in the technology of mechanically driven corers for investigating terrestrial deposits, and in the design of equipment for extracting long sediment sequences from deep lakes (see below).

Although there have been methodological advances in most aspects of the study of the Quaternary stratigraphical record, areas where particular progress have been made are the classification and interpretation of cold climate deposits; the analysis of aeolian, fluvial and lacustrine sequences; the reconstruction of Quaternary sea-level history; and the application of stable isotope analysis to Quaternary terrestrial materials. In the 1960s, observations of active processes operating in contemporary ice-marginal zones of polar glaciers prompted a paradigm shift in the interpretation of mid-latitude glacigenic sequences (Boulton 1972). The realization that complex stratigraphic sequences can result from a single phase of ice wastage led to a re-evaluation of many Quaternary depositional records that had, hitherto, been interpreted as a product of multiple glacial events (Boulton 1977). This work paved the way for new approaches to the study of glacial sedimentary records linking, in particular, processes operating at the glacier bed (notably deformation) with macro- and micro-scale structures in Quaternary sedimentary sequences. Techniques hitherto applied only to the hard-rock geological record, such as facies analysis and sequence stratigraphy, have provided new insights into the nature of former glacial depositional environments. These range from the interpretation of small-scale structural features within individual sections, to the identification of past glacial landsystems in which the geomorphology and sub-surface materials that characterize a landscape are genetically related to the processes involved in their development (Benn & Evans 1998).

Major achievements in glacial geology over the course of the last 50 years include the interpretation and correlation of glacial sediments to produce detailed glacial chronologies for many areas of the world (Sibrava *et al*. 1986), and increasingly accurate determinations of the extent, dimensions and histories of the great continental ice sheets (Denton & Hughes 1981; Ehlers & Gibbard 2004*a-c*). Considerable attention has been focused on the North American (Laurentide) ice sheet (the largest Quaternary ice mass outside Antarctica) during and following the Last Glacial Maximum (LGM: the cold interval centred on 21 ka). Important early work on the pattern of deglaciation of the Laurentide ice sheet (Bryson *et al*. 1969) was followed by further elaboration and refinement (Andrews 1987; Dyke & Prest 1987), with the most recent compilation (Dyke *et al*. 2002; Andrews & Dyke 2007) providing a detailed spatial and temporal reconstruction of the history of the ice sheet (Fig. 2). Equally important has been research in the High Arctic, where, after more than a century of debate, a consensus has emerged that a substantial Innuitan ice sheet covered much of the Canadian Arctic archipelago at the LGM (Dyke *et al*. 2002), and to the north of the Eurasian landmass, work over the past 30 years has shown that a major ice sheet developed over the Barents and Kara Seas, not only during the LGM (Mangerud *et al*. 2002), but also during earlier cold stages (Svendsen *et al*. 2004). These reconstructions of ice-sheet history have been augmented by glacier and ice-sheet modelling, which is described below.

Advances in the interpretation of cold-climate phenomena also extend to the periglacial record. A number of these have arisen from field monitoring and laboratory experimentation in relation to freeze–thaw processes associated with engineering and related activities in permafrost regions (Williams 1979). Others, however, have come from major fieldwork programmes in both high-latitude and high-altitude environments, which again have led to important reappraisals of Quaternary periglacial phenomena. Of particular significance for the interpretation of Quaternary cold climate depositional sequences, for example, has been the recognition of the importance of paraglacial processes, accelerated geomorphological activity that occurs in highly unstable recently deglaciated terrain and that generates extensive suites of sediment that frequently intercalate with glacigenic deposits in the Quaternary stratigraphical record (Ballantyne 2002). Also important has been the empirical relationships that have been established between contemporary periglacial phenomena and prevailing mean annual air temperatures (MAATs), thus allowing quantitative estimates of former air temperatures to be derived from a range of Quaternary relict periglacial phenomena, including ice wedge casts, involutions and pingo scars (Ballantyne & Harris 1994).

Aeolian, fluvial and lacustrine sedimentary sequences are three of the most important Quaternary terrestrial archives because they can provide lengthy and often continuous records of climate and environmental change. Aeolian deposits have long attracted the attention of Quaternary scientists, but it is only in the last 30 years or so that the significance of aeolian materials and their interbedded soils, the latter representing periods of landscape stability under warmer and more humid (interglacial) conditions, has been realized. Flint (1957), for example, described loessic sediments in North America and Europe, but said relatively little about the palaeoenvironmental value of these deposits, or about loess stratigraphy. The major breakthrough came in the 1970s with the first systematic studies of the great loess sequences of central and eastern Asia (Kukla 1987; Derbyshire 1995). The result has been the generation of a series of remarkable high-resolution, chronologically well-constrained records of long-term climate change (Fig. 3), some of which extend back to the beginning of the Quaternary and beyond (Sun *et al*. 2006).

River terrace sequences also have a long history of investigation, but again it is only over the course of the past 20–30 years that the importance of these records has been fully recognized. Morphological and lithostratigraphic analysis of fluvial sequences has revealed that, in well-integrated river systems in formerly glaciated mid-latitude regions at least, aggradation during cold-climate (glacial) phases gives way to incision during

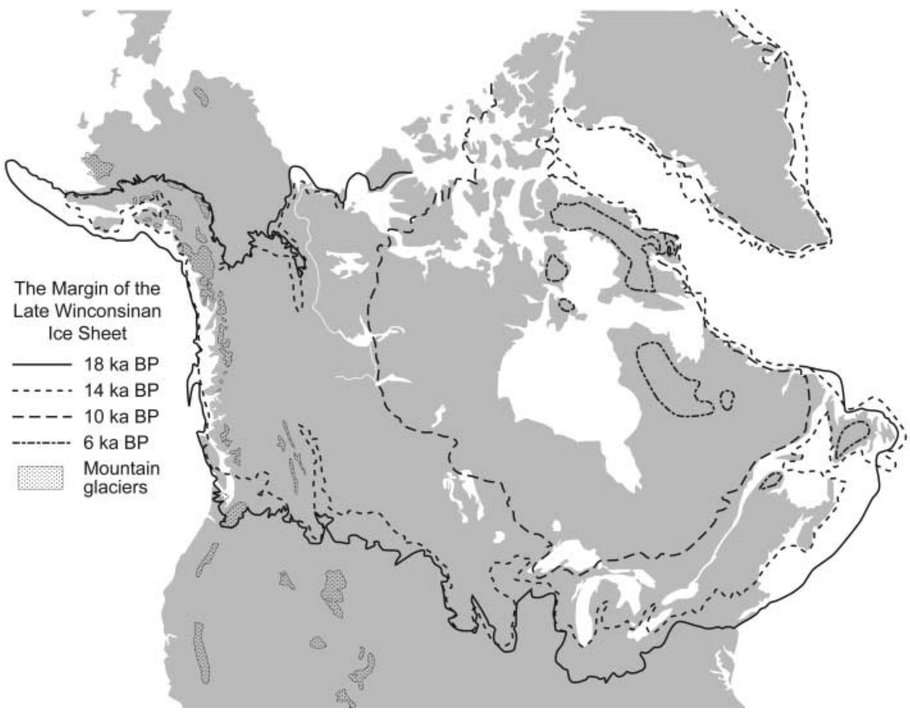

Fig. 2. Isochrons (dates in radiocarbon years bp) for the retreat of the Laurentide, Cordilleran and Innuitan ice sheets at the end of the last glacial stage (after Andrews & Dyke 2007).

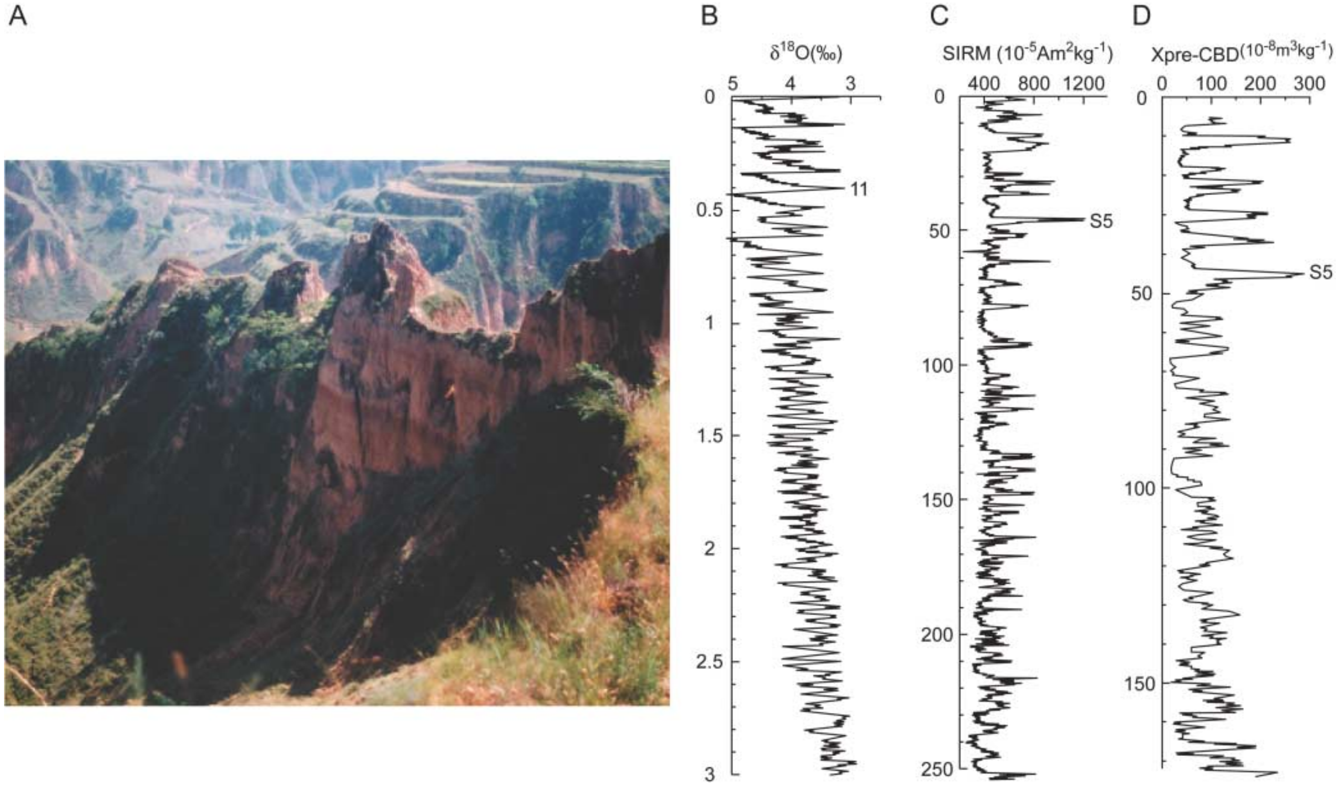

Fig. 3. (**a**) An exposure through a loess (lighter sediments) and palaeosol (darker hues) sequence at Luochuan, Central Loess Plateau, China (photograph by B. Maher). (**b**) The stacked marine oxygen isotope record (see Fig. 4). (**c**, **d**) Magnetic susceptibility records of the Jingbian (**c**) and Jiaodao (**d**) loess–palaeosol profiles (after Liu *et al*. 2007). The inflections in the magnetic susceptibility curves reflect alternations between loessic units (cold stage) and palaeosols (warm stage), and match closely the glacial–interglacial oscillations in the marine isotope sequence.

the intervening temperate (interglacial) periods. As a result, a detailed history of fluvial activity is often preserved in terrace sequences, and this reflects patterns of long-term climate change and/or regional tectonic activity (Meyer & Stets 2002; Westaway *et al*. 2006). In the Mediterranean region, for example, an area where there are some of the best long proxy-climate archives in the world (e.g. Tzedakis 1994; Allen *et al*. 1999; Roberts *et al*. 2001) and where major advances have been made in recent years, a detailed correlation has been established between climate change and fluvial sequences over the course of the last 200 ka (Macklin *et al*. 2002). In the Somme Valley of northern France, there is a fluvial record spanning the past 1 Ma (Antoine *et al*. 2000), and in the Rhine Valley a staircase of fluvial terraces dates back to the Pliocene (Boenigk & Frechen 2006). Even longer archives, in some cases extending into the Miocene, are found in the valleys of the Dneister, Dneiper, Don and Volga river systems of eastern Europe (Matoshko *et al*. 2004).

Some lake basins also contain long and, in many cases continuous, sedimentary records. In southern Europe, for example, there are lacustrine sequences that span several glacial–interglacial cycles (Tzedakis 1994; Reille *et al*. 2000). Lake Baikal, the largest and deepest lake in the world, has yielded a core record extending back over 1 Ma (Prokopenko *et al*. 2001), and the sediments in Lake Biwa, Japan, contain a vegetational and climatic history spanning 3 Ma (Fuji 1988). Long environmental records have also been obtained from palaeolake deposits, including the 3.5 Ma core sequences from the Hula Basin in Israel (Horowitz 1989), and Funza in Colombia (Hooghiemstra & Saarniento 1991). In many present and former low-latitude lakes, water budgets are controlled largely by rainfall (‘pluvial lakes’), and hence variations in lake level (reflected in both sediment and shoreline sequences) allow inferences to be made about past rainfall patterns (e.g. Street & Grove 1979; Smith & Street-Perrott 1983; Harrison & Dodson 1993). In recent years, a number of global databases of past lake-level variations have been developed, mainly for use in model-climate validation (see below), and these provide valuable overviews of past climatic patterns and trends (e.g. Viau & Gajewski 2001; see also http://www.nqdc.noaa.gov/paleo/).

The history of global sea level has been a longstanding theme in Quaternary science, and again progress over the past 50 years in understanding the spatial and temporal patterns of sea-level change has been considerable. This is partly due to more sophisticated approaches to the analysis of evidence for former sea levels involving, for example, combinations of field mapping, field measurement and remote sensing, the integration of geomorphological, lithological and fossil data, and the application of a wide range of dating methods. These various developments have allowed sea-level histories to be reconstructed at a range of spatial scales and often at very high levels of temporal resolution (e.g. Lambeck *et al*. 1998; Shennan & Horton 2002). Recent advances in studies of land and sea-level change also reflect progress in the understanding of processes of crustal rheology, notably glacio-isostasy and neotectonics (Owen *et al*. 1993). Important early contributions by Andrews (1970) and others working on glacio-isostatic changes in the Canadian High Arctic laid the basis for the subsequent modelling of sea-level and ice-sheet interactions (Clark & Mix 2002). Such models not only provide important insights into sea-level history, but also form the basis for predictions of future sea-level change under different scenarios of global warming (Church & Gregory 2001).

Although the potential of stable isotope records as palaeoclimatic indicators was first discussed more than 50 years ago, it was only with developments in mass spectrometric techniques from the early 1970s onwards that stable isotope geochemistry of lake sediments, lake microfossils, tree-ring cellulose, speleothems and bone has become a routine method for reconstructing Quaternary climate change (Leng 2004). Experimentally determined fractionation factors have allowed quantitative relationships to be established between isotopic ratios and controlling climatic parameters, which allow the isotopic signal to be read as a proxy climate record. Some of the most significant advances in recent years have been in isotope dendroclimatology, where stable isotopes of carbon, oxygen and hydrogen in individual tree rings allow annually resolved temperature and precipitation records to be reconstructed (McCarroll & Loader 2004), and in speleothems, where much longer precisely dated stable isotope records provide a basis for correlation between terrestrial, ocean and ice-core records (Spötl *et al*. 2002; Burns *et al*. 2003). These offer a realistic means of assessing leads and lags in the climate system and, as such, constitute important inputs to global climate models (see below).

Biotic evidence. In the 1950s, work on Quaternary terrestrial fossils was restricted mainly to pollen, plant macrofossils, vertebrate bones and molluscs. Although Flint tended to consider fossil evidence principally as a basis for correlation, others took a wider view, with the magisterial volume *History of the British Flora* by Godwin (1956) perhaps best exemplifying the increasing interest in vegetational history and in other aspects of the Earth's biotic record. Since then, that interest has expanded to the extent that palaeoecology has become a central theme in Quaternary science, providing data on landscape change at a range of spatial and temporal scales; on faunal and floral distributions; on plant and animal migrations and evolution; on human–landscape interactions; and on climate history (Lowe & Walker 1997; Willis *et al*. 2004).

Amongst the many methodological and technological innovations in Quaternary palaeoecology over recent decades, there are four areas in particular where important progress has been made. The first is in the much wider range of fossil organisms now actively being investigated compared with 50 years ago. To the fossil evidence described above can be added such diverse elements as freshwater algae (diatoms, charophytes, chrysophytes), cladocera and freshwater ostracodes, all of which provide evidence on habitat changes in aquatic ecosystems (Smol *et al*. 2002); midges (Diptera; Chironomidae), from which quantified palaeotemperature inferences can be inferred (Elias & Walker 2006); testate amoebae (Rhizopods), which can be employed as palaeoprecipitation indicators (Charman *et al*. 2000); and charred particles (charcoal), which represent evidence of burning, often related to human activity (Mellars & Dark 1998). Of particular importance has been research on fossil beetles (Coleoptera), where the pioneering work of Russell Coope (Coope & Brophy 1972; Atkinson *et al*. 1987) revealed the rapid nature of late Quaternary climate change fully 20 years before its subsequent demonstration in the ice-core record (see below). Advances in techniques of sample recovery, in fossil extraction, and in microscopy (including the use of both light- and electron microscopes), have been allied to progress in taxonomy and in the understanding of the controlling environmental parameters that determine distribution. Accompanying these developments has been an increasing trend towards multi-proxy research programmes, in which palaeoecological reconstructions are based on multiple lines of fossil evidence, and where the fossil record is integrated with other climatic–environmental proxies, such as stable isotope data (Ammann 2000; Walker *et al*. 2003).

A second important development has been the increasing application of quantitative methods to Quaternary palaeoecological data (Imbrie & Kipp 1971; Birks & Gordon 1985; Birks 1998). These approaches have been used, *inter alia*, to derive more rigorous definitions of ecological assemblage zones in pollen, plant macrofossil and diatom diagrams; to analyse complex datasets using multivariate statistical methods to identify ecological interrelationships and controlling environmental parameters in, for example, lacustrine ecosystems; and to provide a quantitative basis for palaeoclimatic reconstructions. The last named is an important aspect of recent Quaternary research and involves the application of a statistically based modern analogue approach to the recent fossil record. Contemporary plant or animal data are calibrated to climatic parameters using transfer functions, and the derived 'training sets' allow quantified estimates of past climatic conditions (temperature and precipitation) to be inferred from, for example, the pollen, chironomid, diatom or testate amoebae record (Huntley 1993; Walker & Cwynar 2006). A quantitative approach to the analysis of the Quaternary fossil record has also been important in the formulation and calibration of numerical models (see below), in testing hypotheses relating to Quaternary plant and animal migrations, and in the context of recent advances in ecological theory (Seppä & Bennett 2003).

A third aspect of the Quaternary fossil record where there have been significant recent developments has been in the study of ancient DNA. It had previously been believed that DNA molecules were rapidly destroyed after the death of an organism, but this view changed in the 1980s when the first fragments of ancient DNA were recovered from archaeological specimens (Higuchi *et al*. 1984). Subsequent advances in molecular biology have made it possible to obtain ancient DNA sequences from well-preserved Quaternary fossils, and these can inform many aspects of Quaternary research, including systematics and phylogeny, conservation biology, evolutionary theory and molecular taphonomy (Yang 1997). In archaeology, DNA offers an exciting new tool for testing hypotheses about human migrations (Olivieri *et al*. 2006), and about human evolutionary history, such as the relationships between Neanderthals and modern humans (Ovchinnikov *et al*. 2000; Green *et al*. 2006). Other applications include studies of palaeodisease, kinship and population studies, and the origins of animal domestication (Brown 2001). The recovery of plant and animal DNA from permafrost and from cave sediments indicates the potential for reconstructing palaeonvironments from these genetic signals (Willerslev *et al*. 2003), and recent research has shown how the timing of genetic mutations revealed by DNA analysis can be used as a 'molecular clock' to date key events in human evolution (Chou *et al*. 2002).

A fourth area of the Quaternary fossil record where major progress has been made over the course of the past 50 years has been in archaeology and palaeoanthropology, particularly in our understanding of spatial and temporal patterns of human evolution and dispersal. Although some researchers continue to subscribe to a 'multi-regional' notion of human evolution (Wolpoff & Caspari 1997), there has been growing support in recent years for the 'Out of Africa' model, the idea that modern humans originated in Africa and spread out from there (Stringer 2003). Major discoveries of early hominid remains older than 2 Ma at sites in the East African Rift Valley, and in caves in South Africa have, in the view of many, provided strong confirmatory evidence for this hypothesis (Strauss & Bar-Yosef 2001). That early hominids left Africa prior to 1.5 Ma is indicated by important fossil finds in Java and Georgia with ages of 1.7–1.9 Ma (Swisher *et al*. 1994; Gabunia *et al*. 2000). Evidence from northern Spain dates the oldest human presence in Europe to *c*. 780–980 ka (Parés & Pérez-González 1999), and new artefactual evidence from the East Anglian coast places the earliest human colonization of the British Isles and northern Europe at around 725 ka (Parfitt *et al*. 2005). It has become increasingly apparent, however, that there was a later exodus of anatomically modern humans from Africa, sometime between 60 and 100 ka, and it is from this wave of dispersal and not from earlier ones, that modern humans now seem likely to be descended (Krings *et al*. 1997). In the New World, the prevailing view of the past 50 years has been that the peopling of the Americas occurred principally at the end of the last (Wisconsinan) cold stage following the wastage of the northern ice sheets (the 'Clovis' model), although more recent artefactual and fossil discoveries, along with the re-evaluation of existing chronologies, have now raised the possibility of an earlier date for human colonization of the New World (Marshall 2001; Waters & Stafford 2007). There is a similar debate over the timing of human arrivals in Sahul (Australia and New Guinea), the conventional opinion being that colonization occurred after 45 ka (O'Connell & Allen 2004), whereas others have argued for human presence several thousand years earlier (Turney *et al*. 2001). In terms of evolution, enormous progress has been made over the last 50 years in understanding human origins (Stringer 2002), although recent discoveries, such as the skeletal remains of what are believed to be of a now-extinct miniature hominin on the island of Flores in Indonesia (Brown *et al*. 2004), continue to add new perspectives to this important area of research.

The marine record

The first systematic investigations of deep-ocean sediments date from the 1930s, but the modern phase of deep-sea research began in the 1950s with the development of corers mounted on specially equipped drilling ships that were capable of recovering undisturbed sediment cores of 10 m and more in length. For the first time, continuous sedimentary records were available that spanned the entire range of Quaternary time. Data from these core sequences have revolutionized Quaternary science, offering penetrating new insights into ocean circulation and temperature changes, into climatic variability, into ocean–atmosphere–ice-sheet interactions, and into the causal mechanisms of long-term climate change, as well as providing a basis for global time-stratigraphic correlation.

In terms of its impact on Quaternary science, the most important aspect of deep-ocean sediment research has almost certainly been the analysis and interpretation of the marine stable isotope record (Maslin & Swann 2006). Carbon isotopes in planktonic Foraminifera, for example, have provided key data on productivity changes in the upper layers of the oceans and potential linkages with atmospheric variations in CO_2 (Shackleton *et al*. 1992), and $\delta^{13}C$ signatures in benthic Foraminifera have been used to reconstruct histories of deep-water circulation changes (Moreno *et al*. 2005). Most far-reaching of all, however, has been the derivation of an oxygen isotope record ($\delta^{18}O$) that reflects past changes in the isotopic composition of ocean waters (Fig. 4). Initially interpreted as reflecting variations in water temperature, the foraminiferal $\delta^{18}O$ signal was subsequently shown, in one of the key papers of the last 50 years, to be dominated by an ice-volume component, so that fluctuations in the oxygen isotope signal should be read not as a palaeotemperature, but rather as a palaeoglaciation record (Shackleton & Opdyke 1973). Episodes of expanded land ice (glacials), when substantial quantities of the lighter isotope ^{16}O were locked into the ice sheets, are reflected in the marine isotopic profile by shifts to heavier $\delta^{18}O$ values, whereas lighter $\delta^{18}O$ values characterize interglacial periods when land-ice volumes were markedly reduced. Downcore variations in $\delta^{18}O$ therefore provide a continuous record of climate change, with more than 50 glacial–interglacial cycles now identified during the course of the Quaternary (Shackleton *et al*. 1990), a number that would have been considered inconceivable only 50 years ago. Not only does the marine oxygen isotope sequence provide a coherent climate signal (Huybers 2006), it also provides strong confirmatory evidence for the theory that the Earth's climatic rhythms are responding primarily to astronomical influences (see below). Insofar as the isotopic signal is a reflection of changes in land ice volume, it also constitutes a proxy for global sea-level change (Shackleton 1987). More importantly, however, it offers a basis for time-stratigraphic correlation, for research over the past four decades has revealed a remarkable similarity between the isotopic profiles from different parts of the world's oceans in terms of both the number and amplitude of oxygen isotope cycles (Elkibbi & Rial 2001). The common peaks and troughs in the curves have therefore been designated as marine isotopic stages (Fig. 4), and as the inflections and key boundaries ('terminations') between the stages are essentially time-parallel events (Broecker 1984), these form the basis for correlation at the global scale. The time scale for the marine isotope sequence is based either on geomagnetic boundaries in core sequences or on the tuning ('orbital tuning') of the isotopic signal to the known frequencies of the astronomical variables (see below) (Martinson *et al*. 1987). The marine oxygen isotope record now provides the global stratigraphic template for the past 3 Ma, and its development represents one of the greatest achievements of late twentieth century Quaternary science (Lisiecki & Raymo 2005).

In addition to advances in stable isotope analysis, there have also been important developments in the use of marine microfossils as palaeoceanographical indicators. A wide range of fossils is now routinely used to infer ocean temperature and circulation changes. These include Foraminifera, Radiolaria, coccolithophores and diatoms, and recent advances in chromatographic techniques mean that long-chain carbon compounds (C_{37-39} or U^{k}_{37} alkenones) derived from microfossil remains such as coccoliths provide an alternative approach to ocean palaeotemperature reconstruction (McClymont *et al*. 2005). Chemical 'tracers' in marine microfossils are also being increasingly used to infer palaeoceanographical conditions. For example, Cd/Ca ratios in foraminiferal tests have been employed as a proxy for nutrient (P) levels to detect past variations in ocean productivity linked to changes in deep-water formation (Keigwin *et al*. 1991), and histories of ocean-surface temperatures have been reconstructed from Mg/Ca ratios in planktonic Foraminifera (Barker *et al*. 2005). Over recent decades, a wide range of other chemical and biological 'proxies' has been developed which now allow past surface, intermediate, and deep-ocean conditions to be analysed, often in great detail (e.g. Kucera *et al*. 2005; De Vernal *et al*. 2006).

The systematic investigation of late Quaternary ocean temperatures began in the 1960s and initially employed downcore variations in the abundance of obligate cold- and warm-water

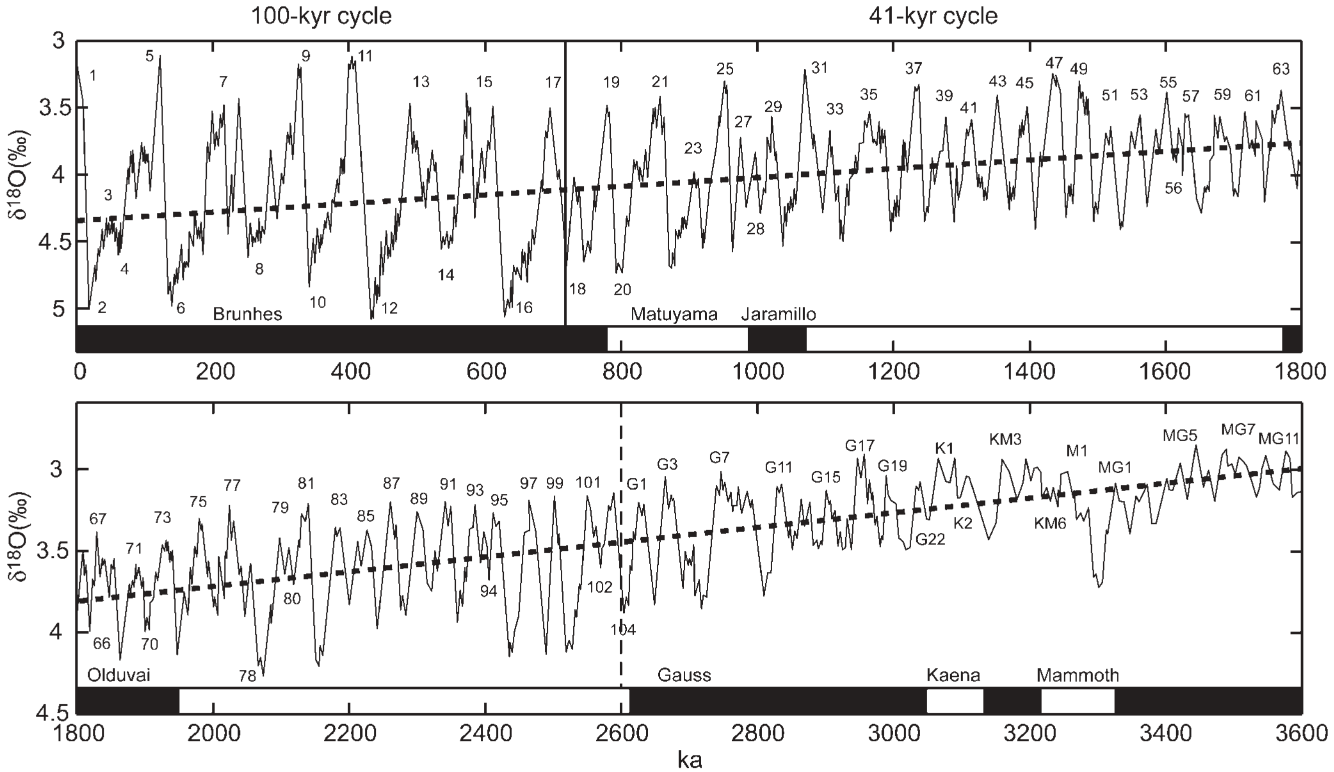

Fig. 4. A composite oxygen isotope curve for the last 3.5 Ma, constructed by 'stacking' (cross-correlating) 57 globally distributed benthic marine $\delta^{18}O$ records, and shown against the palaeomagnetic time scale (after Lisiecki & Raymo 2005). Odd numbers denote interglacial isotopic stages, and even numbers glacial isotopic stages. Noteworthy features are the long-term decline in mean temperature (dotted line) and the tendency to higher-amplitude climatic fluctuations over time, with pronounced shifts at *c*. 2.6 Ma (dotted vertical line) and at *c*. 700 ka (continuous vertical line). The latter is accompanied by a switch in dominance from the 41 ka to the 100 ka astronomical cycle.

species to infer past ocean temperature change and to reconstruct the spatial and temporal migration of major ocean water masses and associated atmospheric frontal systems (Ericson & Wollin 1968). As in the analysis of the terrestrial data, however, a major development in marine micropalaeontology in the 1970s was the increasing adoption of quantitative methods to aid in the interpretation of the marine fossil record. The seminal work of Imbrie & Kipp (1971), who used transfer functions to derive palaeotemperature estimates, not from individual fossils but from planktonic foraminiferal assemblages, was an important milestone in Quaternary palaeooceanography, and refinements to this approach have provided the basis for most subsequent research into past ocean water temperature variations. Quantitative palaeoceanography has been a key feature of a series of integrated research programmes whose aims have been to reconstruct ocean-surface conditions for particular time periods during the late Quaternary, and to link those data to reconstructions of terrestrial and climatic environments. The first of these initiatives involved simulations of the ocean–atmosphere system at the 'Last Glacial Maximum' (CLIMAP Project Members 1976, 1981), and was followed by a multi-disciplinary research programme focusing on insolation variations and ice-sheet, oceanographic and other Earth-surface responses over the past 18 ka (COHMAP Members 1988). More recent programmes include EPILOG (Environmental Processes of the Ice age: Land, Oceans, Glaciers), launched in 1999 (Mix *et al*. 2001), and MARGO (Multi-proxy Approach for the Reconstruction of the Glacial Ocean surface) that followed 3 years later (Kucera *et al*. 2005). These wide-ranging, collaborative research projects not only provide important new insights into past ocean-surface changes and ocean–atmosphere–cryosphere linkages, but they also generate key baseline data for the calibration of models of the late Quaternary global system (see below).

Such linkages between the marine record and other components of the terrestrial–climate system have been an important theme in recent Quaternary research. A significant development in this respect was the discovery in the 1980s of layers of ice-rafted debris in sediment cores from the North Atlantic (Heinrich 1988). These 'Heinrich Events' are considered to be related to the periodic discharge of icebergs from both the Laurentide and Fennoscandian ice sheets between *c*. 14 and 70 ka BP (Bond *et al*. 1992). Subsequent work has shown that the 'Heinrich Events', which resulted in extreme cooling of surface waters through a combination of meltwater influx and drifting ice, are the end-members of a series of cooling cycles (Bond cycles: see also Dansgaard–Oeschger cycles below) that occurred in the North Atlantic region during the last cold stage (this corresponds to the Weichselian in Europe, the Devensian in Britain and the Wisconsinan in North America, and is broadly equivalent to Marine Isotope Stages 2–4 in the deep-ocean record) but whose effects may have been global in terms of their impact (Hemmings 2004). The Heinrich layers in North Atlantic sediments reflect extreme events that can result from a complex interaction between the ocean, ice sheets and atmosphere, and that may induce reorganizations of the global climate system on millennial time scales (see below). Recent research on the North Atlantic has also revealed periodicities in the Holocene marine record, with the identification of a cycle centred on *c.* 1500 years that can be traced back into the last cold stage (Bond *et al.* 1997), with 550 and 1000 year cycles also evident in other marine records (Chapman & Shackleton 2000). The fact that these periodicities are now being detected in terrestrial proxy climate records (e.g. Hughes *et al.* 2000; Viau *et al.* 2002; Hu *et al.* 2003) suggests a short-term regularity or rhythm in the Earth's climatic system that is, as yet, not fully explained (although see Sub-Milankovitch events, below).

Ice-core records

Alongside advances in deep-ocean research in the second half of the twentieth century has been the coring of ice sheets and glaciers. The first deep cores were obtained from Camp Century in Greenland in the 1960s, since when drilling has been carried out at a number of sites in Greenland and Antarctica, as well as on smaller ice caps in the Canadian Arctic and on low-latitude mountain glaciers. Ice cores contain a wealth of palaeoclimatic and palaeoenvironmental data including a record of atmospheric trace gases trapped in ice bubbles; of past variations in atmospheric particulate matter, such as dust and volcanic ash; of variations in stable isotopes; and of a range of other trace substances. These records are dated by annual accumulations of snow using either visible stratigraphy (counting of ice layers) or 'multi-parameter' analysis of seasonal variations in stable isotopes, major chemical elements, or electrical conductivity (Meese *et al.* 1997). In deeper ice, where seasonal layers are smoothed by diffusion during the conversion of snow to ice, age estimates are obtained from ice-flow models. The Greenland ice-core sequence extends back to the last interglacial at around 120 ka (North Greenland Ice Core Project Members 2004), whereas in Antarctica, slower rates of snow accumulation allow much longer records to be obtained, the longest to date being the EPICA core, which already extends back over 800 ka and may eventually reach almost 1 Ma (EPICA Community Members 2004). Shorter records are preserved in glacier ice in mountain regions where, in some cases, radiocarbon dates on organic material near the ice–bedrock contact provide a maximum age for the basal ice (Thompson *et al.* 2005).

Data from ice cores have been used, *inter alia*, to reconstruct changes in atmospheric circulation; former temperature and precipitation regimes; and histories of volcanic activity; as well as in investigations of human impact on the global climate system (Mayewski & White 2002). Some of the most remarkable discoveries, however, relate to the instability of past climate, to the rapid nature of past climate change, and to hemispherical variations in past climates. Prior to 1990, the prevailing view had been that the climatic regime of the North Atlantic region during the last cold stage had been largely one of unremitting cold, interrupted only by occasional short-lived interstadial espisodes. Oxygen isotope data from the Greenland ice cores (notably from GRIP, GISP2 and NGRIP) have shown, however, that this is far too simplified a view of climate history, for no fewer than 25 major climatic fluctuations appear to have occurred at regular or quasi-regular intervals (Fig. 5), and with an amplitude of up to 15 °C (Johnsen *et al.* 2001). Rapid warming (in some instances in <50 years) was followed by more gradual cooling over cycles lasting between 500 and 2000 years. These major climatic fluctuations, known as Dansgaard–Oeschger cycles, appear not to have been confined to Greenland and the North Atlantic, but are registered in records from as far away as the tropical Atlantic (Fig. 6), the Mediterranean, China and Antarctica (Leuschner & Sirocko 2000). They are thought to reflect a combination of feedback mechanisms involving ice-sheet fluctuations, oceanographical changes and atmospheric circulation variations (see Bond cycles above). The climatic fluctuations (stadials and interstadials) reflected in the Greenland oxygen isotope record also constitute an 'event stratigraphy' for the last cold stage in the North Atlantic region (Björck *et al.* 1998), which offers a basis for correlation between terrestrial, marine and ice-core records (Rousseau *et al.* 2006).

A further feature of the isotopic signal in the ice cores is an apparent global-scale anti-phase relationship, whereby cooling in Antarctica coincides with warming in Greenland and vice versa, a phenomemon that has been termed the 'Bipolar Seesaw' (Broecker 1998). Correlations between well-resolved ice-core records from Greenland and Antarctica confirm the consistency of this trend throughout the last glacial cycle (EPICA Community Members 2006). Although the driving mechanisms behind the

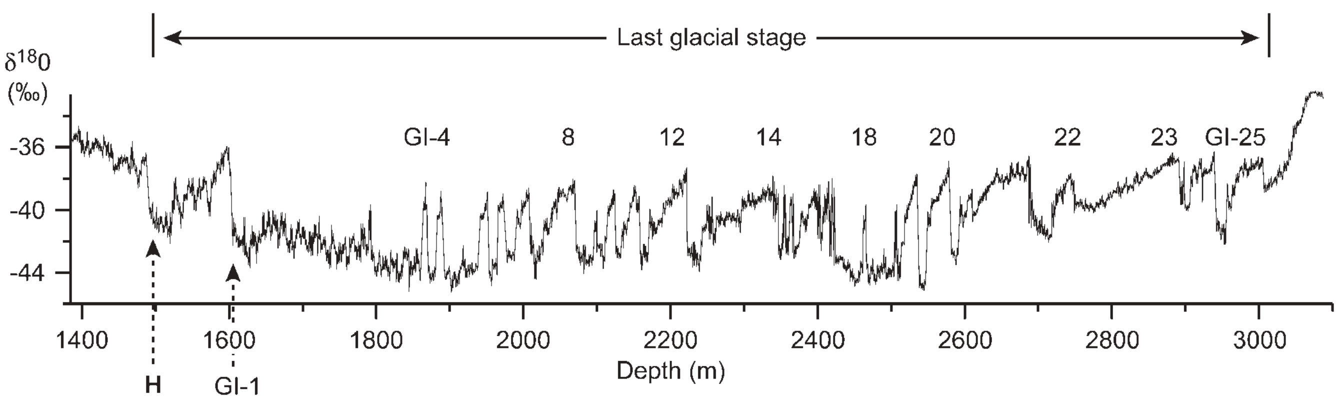

Fig. 5. Oxygen isotope variations in the NGRIP ice core between 1400 and 3100 m depth, spanning the period *c.* 9–120 ka (from Svensson *et al.* 2005). H marks the onset of the Holocene at *c.* 11.7 ka; GI-1 is the start of Greenland Interstadial 1 at *c.* 14.7 ka. The last cold stage is characterized by at least 25 abrupt interstadial warmings (Dansgaard–Oeschger events), numbered sequentially from top down (GI-1 to GI-25), which reflect temperature fluctuations over Greenland of between 9 and 15 °C. Most of these warmings occurred within a few decades, and the initial warming at the start of the Holocene may have taken less than 20 years.

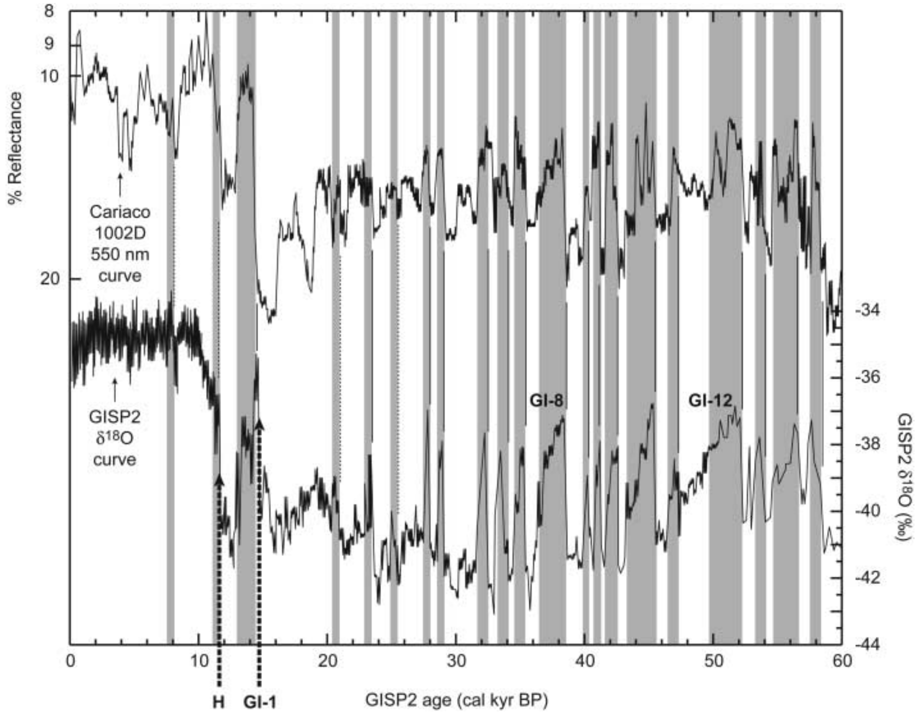

Fig. 6. Comparison between the GISP2 Greenland $\delta^{18}O$ record over the last 60 ka (upper) and the sediment record from the Cariaco Basin off the coast of Venezuela (lower). The Dansgaard–Oeschger events in the ice-core sequence correlate closely with variations in colour (measured as per cent reflectance of incident light) of the annually laminated sediments in the Cariaco Basin, the colour changes being related to variations in productivity in the marine basin (after Peterson *et al*. 2000). The grey-shaded vertical bars pick out the main warming events in both series.

Bipolar Seesaw remain elusive, this remarkable discovery may provide valuable clues about global climatic behaviour, and has far-reaching implications for predicting future climate change.

The world's ice sheets are also unique archives of past changes in atmospheric greenhouse trace gases (GTGs), the longest record so far obtained being the combined Vostok–Dome C (EPICA) profile from Antarctica, which extends back 650 ka (Spahni *et al*. 2005). The Antarctic ice-core records also provide important evidence for recent changes in concentrations of GTGs (Fig. 7a), with present levels in the ice being markedly higher than at any time over the last 400 ka, reflecting the impact on the Earth's atmosphere of recent industrial activity (Raynaud *et al*. 2000). The ice cores may provide an even longer record of human impact on the atmosphere, however, for it has been proposed that an increase in CH_4 concentrations in the Vostok core around 5 ka (Fig. 7b) relates to early rice farming and enhanced CH_4 emissions from flooded fields (Ruddiman & Thompson 2001), and that the increase in atmospheric CO_2 from around 8 ka could be attributable to human-induced deforestation (Ruddiman 2005). Indeed, anthropogenic impact on climate over the last several thousand years may have been sufficient to offset the natural cooling trend that is part of the long-term climatic cycle, and effectively to delay the onset of the next glaciation (Ruddiman 2003). This remains a controversial view, however, and other mechanisms for changes in atmospheric CO_2 (e.g. increase in terrestrial biomass) have been suggested (Broecker *et*

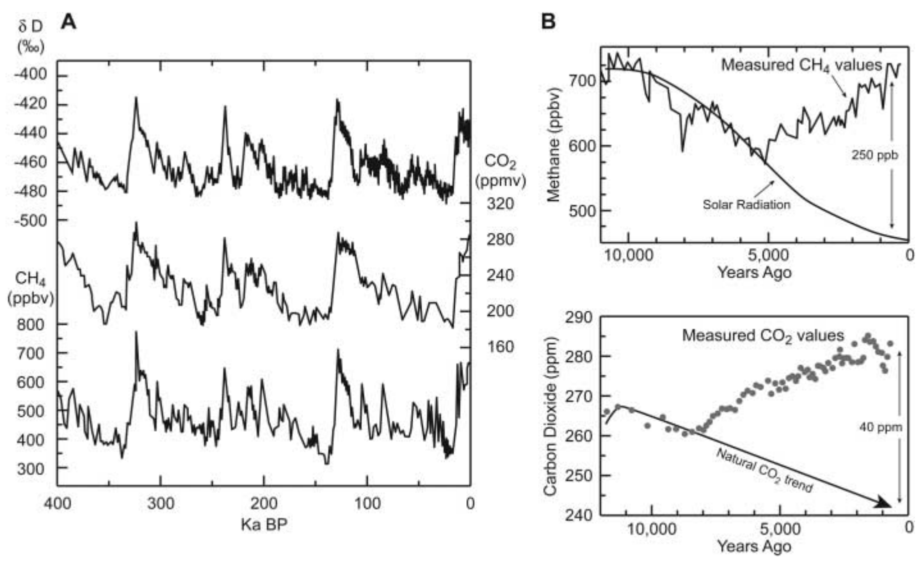

Fig. 7. (**a**) The Antarctic ice-core record of global climate over the past four glacial–interglacial cycles as reflected in δD variations (upper), and in atmospheric CO_2 (middle) and CH_4 concentrations (lower) (after Raynaud *et al*. 2000). The close correspondence between fluctuations in δD (temperature) and in the two 'greenhouse' gases should be noted. (**b**) Atmospheric CH_4 (upper) and CO_2 variations (lower) during the present (Holocene) interglacial in the ice-core records. In contrast to earlier interglacials, CH_4 levels diverge markedly from solar radiation trends during the later Holocene, and measured CO_2 values also diverge from the natural CO_2 trend (after Ruddiman *et al*. 2005). These differences have been attributed to the beginnings of rice farming at *c*. 5 ka (increased methane release from paddy fields), with possible earlier human effects (deforestation, etc.) also reflected in the CO_2 departure from the natural signal from *c*. 8 ka onwards.

al. 2001). Whatever the causal mechanisms, evidence in ice core data from Tibet, East Africa and the Andes show that the current warming at high elevations is unprecedented for at least the last 5 ka, an almost inevitable consequence of which is that most low-latitude glaciers seem likely to disappear in the very near future (Thompson *et al*. 2006).

Understanding Quaternary climate change

The rich array of data preserved in the various Quaternary archives not only provides convincing evidence for the cyclical nature of Quaternary climate, but also offers important insights into the possible causal mechanisms of climate change. Indeed, one of the most striking achievements of Quaternary science during the course of the last 50 years has been the progress that has been made towards an integrated theory of long-term climate change, the central tenet of which is that the glacial–interglacial cycles of the Quaternary are driven primarily by astronomical influences, namely variations in the Earth's orbit and axis.

The Astronomical Theory of climate change

First developed by James Croll over 100 years ago, and ingeniously elaborated by Milutin Milankovitch in the 1920s, the Astronomical Theory (or Milankovitch Theory) invokes changes in orbital eccentricity (95–136 ka cycle), variations in axial tilt or 'obliquity' (41 ka cycle) and precession (19–23 ka cycle) to explain past changes in solar radiation receipt and distribution of that heat energy, and hence to account for global temperature change though time. Although initially accepted by many in the geological community, within 30 years the Milankovitch Hypothesis had been almost universally rejected (Imbrie & Imbrie 1979). Flint, for example, concluded that 'the geometric scheme of distribution of insolation heating must be considered inadequate in itself to explain the Pleistocene climatic changes' (Flint 1957, p. 509).

In the late 1960s, however, work initially on sea-level change and subsequently on deep-ocean sediments led to a renewed interest in the Astronomical Theory. U-series dates on coral reefs in Barbados showed sea-level highstands (reflecting warmer episodes) at around 82 ka, 105 ka and 125 ka, which coincided closely with the phasing of the precessional cycle (Mesolella *et al*. 1969), and in perhaps the most important Quaternary paper of the past 50 years, Hays *et al*. (1976) described cycles of 100 ka, 43 ka, 24 ka and 19 ka duration in marine oxygen isotope sequences, which provided the first unequivocal evidence of the Milankovitch climatic rhythms in the recent geological record. Subsequently, Milankovitch cycles have been detected in proxy records from such diverse sources as coral reef sequences (Aharon 1984), lake deposits (Trauth *et al*. 2001), loess or palaeosol profiles (Sun *et al*. 2006), and the Antarctic ice sheet (EPICA Community Members 2004).

Although these data appear to offer strong confirmatory evidence for the hypothesis that changes in the Earth's orbit and axis are the primary driving mechanism in Quaternary climatic change (Imbrie *et al*. 1992), it has become increasingly apparent that there are aspects of Quaternary climate history that cannot be explained by the Milankovitch Theory alone, and that other factors serve to modulate or amplify the effects of the astronomical variables, often through complex global feedback mechanisms. It is apparent from the marine isotope signal, for example, that the climatic cycles of the Quaternary have not been constant, but have shifted from a periodicity of around 41 ka prior to *c*. 900 ka to a prevailing rhythm of *c*. 100 ka over the course of the last 800–900 ka (Fig. 4). 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 1988).

These changes could be due, in part, to tectonic activity, with the transgression of critical altitudinal thresholds and accompanying changes in atmospheric circulation regime (Raymo & Ruddiman 1992), but they could also involve a complex interplay of Milankovitch forcing (principally on precessional and obliquity time scales) and feedback mechanisms, involving ocean circulation changes, ice-sheet build-up and changing atmospheric gas ratios. One suggestion is that prior to 900 ka, ice sheets melted during each precession or obliquity-induced warm stage, but around 900 ka, Northern Hemisphere temperatures had cooled to a critical threshold, which allowed ice to persist through weaker insolation maxima and hence grow to a larger size over each successive cycle (Raymo 1997). Because high-amplitude precession maxima occur only in every fourth cycle (100 ka), as a result of eccentricity modulation, ice sheets would tend to grow and melt with a periodicity of 100 ka. In an important contribution, Denton (2000) envisaged ice sheets growing steadily over the course of a 100 ka cycle, extracting waters from the world's oceans and leading to major reorganization of deep-water circulation from an 'interglacial' to 'glacial' mode. Astronomical influences eventually trigger ice-sheet collapse, which shifts circulation back into an interglacial mode and the cycle begins again. The role of CO_2 feedback also appears to have been an important factor (Ruddiman 2003). Indeed, Shackleton (2000) has elegantly demonstrated how at the 100 ka periodicity, atmospheric CO_2, air temperature (as reflected in the ice-sheet record) and deep-water temperature are in phase with orbital eccentricity, whereas ice volume lags these three variables. Hence, the effect of orbital eccentricity probably enters the palaeoclimate record through an influence on the concentration of atmospheric CO_2.

Despite the general acceptance of the Milankovitch hypothesis as an explanatory mechanism for Quaternary climate change, there nevertheless remain a number of aspects of long-term climatic history that are puzzling. Doubts have been raised, for example, as to whether the energy associated with the 100 ka signal is sufficient to drive the glacial–interglacial cycles of the past 100 ka, and whether stochastic processes are as important as Milankovitch forcing (Wunsch 2004). Similarly, it is not at all clear why the glacial record should be dominated during the late Pliocene and early Pleistocene by obliquity rather than the stronger precessional signal (Paillard 2006). The cause and effect relationship between the Milankovitch frequencies and climate change has also been questioned (Karner & Muller 2000). Although these and other issues are perhaps unlikely to lead to the replacement of the Astronomical Theory by an alternative explanatory mechanism for long-term climate change, they do suggest that a number of important matters have still to be resolved, and that in Quaternary science the Milankovitch Hypothesis will continue to be debated for some years to come.

Sub-Milankovitch climatic events

In addition to long-term variations in climate during the Quaternary, high-resolution proxy records provide evidence of rapid climatic variations that are superimposed on the orbitally driven cycles. These short-lived sub-Milankovitch events occur over time scales varying from centuries to millennia and have been found, *inter alia*, in ice-core records from Greenland (North

Greenland Ice Core Project Members 2004), in North Atlantic ocean sediments (Bond *et al*. 1997) and in Chinese cave speleothems (Wang *et al*. 2001). Analysis of these and other records has prompted a continuing, and still not fully resolved, debate over the extent to which short-term climate change is driven by external factors, such as solar variability (Renssen *et al*. 2000), or internal factors involving ocean–atmosphere feedback mechanisms and ice-sheet dynamics (Van Krefeld *et al*. 2000).

There is now, however, a general consensus that energy transfer in the world's oceans driven by thermohaline circulation is a major causal factor of climate change on sub-Milankovitch time scales. Of particular importance has been the recognition of the operation of the global conveyor, whereby dense, saline water moves from the Atlantic to the Pacific at depth, and a compensating countercurrent near the surface brings warm water into the North Atlantic (Broecker *et al*. 1985). Ventilation (sinking) of ocean surface waters to form North Atlantic Deep-Water (NADW) releases heat to the atmosphere equivalent to *c*. 25% of the solar heat reaching the surface of the North Atlantic (Broecker & Denton 1990). This conveyor system appears to be inherently unstable, however, and may have been reduced in intensity or shut down altogether by chilling of ocean surface waters during deglaciation (Clark *et al*. 2003), or by iceberg influx during Heinrich events (see above). Indeed, carbon isotope and other indicators of ocean temperature and productivity show abrupt reductions in NADW during the Heinrich events (Elliot *et al*. 2002), pointing to a close link between ocean circulation, ice-sheet behaviour and climate on sub-Milankovitch time scales (Schmidt *et al*. 2006).

Although ocean–ice-sheet interactions provide a persuasive explanatory mechanism for short-term climate changes, other factors are almost certainly involved in the climatic cycles manifest in the late Quaternary record. One potential trigger for short-term climate change is variations in solar energy (Beer *et al*. 2000). Observational data on sunspot cycles, augmented by documentary evidence, provide a history of solar variability over the last four centuries (Stephenson 1990), and this record has recently been extended back into the last cold stage using the cosmogenic isotope signal in tree rings and ice cores (Beer *et al*. 2002). Analysis of these data shows a close correlation between solar variability and the historical climate changes of the Little Ice Age (Lean 1996), and over longer time scales, linkages have been suggested between solar cycles and North Atlantic ocean circulation changes (Bond *et al*. 2001; Van Geel *et al*. 2003). A second trigger may have been volcanic activity. The screening of incoming solar radiation by volcanic dust and particularly by volcanic aerosols from recent volcanic eruptions, and a subsequent reduction in global temperature, was convincingly demonstrated more than two decades ago (Rampino & Self 1982), but a longer-term record of volcanism has since been obtained from acidity profiles in polar ice cores (Zielinski *et al*. 1997). The GISP2 ice-core, for example, shows a significant increase in volcanic activity over the past 600 years, and various proxy climate records indicative of cooling have been linked to this episode of increased volcanism (Briffa *et al*. 1998).

The role of atmospheric trace gases in short-term climate change has also been an increasing focus of attention in recent years. Data from polar ice point to a close relationship between global temperatures, atmospheric levels of CO_2 and δD signatures of ice during the late Quaternary (Siegenthaler *et al*. 2005), with particularly marked changes in trace gas content at glacial–interglacial transitions (Severinghaus *et al*. 1998). Whether trace gas fluctuations are primary drivers of climatic fluctuations, however, or are perhaps reflective of changes in the global carbon cycle, which are themselves a consequence of climatic variations, remains an issue that is still unresolved. The recent discovery that CO_2 fluctuations in the Antarctic ice-core record lag behind Southern Hemisphere temperature change, but precede global ice-volume variations (Mudelsee 2001), is an example of the complex chain of feedback mechanisms that operate within the global environmental system. This is one of the most challenging aspects of contemporary Quaternary science, where advances in understanding have been made not only through an analysis of the empirical evidence, but also through experimentation, and it is to this area of recent Quaternary research that we now turn our attention.

Numerical modelling

Although progress in geochronology, in the recovery and interpretation of evidence from the stratigraphical record, and in our understanding of the causes of long-term climate change, all represent important achievements in Quaternary science over the past 50 years, of equal importance have been advances in the field of numerical environmental modelling. These have been made possible by parallel innovations in digital computing, where computer power and speed of processing have developed to a level that could not have been anticipated by Flint and his geological contemporaries half a century ago. As a consequence, Quaternary scientists now have at their disposal extremely powerful tools that can simulate to an extraordinary degree the natural processes that operate both at the Earth's surface and within the global climatic system.

Perhaps the best known are general circulation models (GCMs) that simulate the workings of global climate. These were first developed more than 40 years ago as relatively simple models of the atmosphere, but now typically consist of integrated multi-component representations of the full climate system (McGuffie & Henderson-Sellars 2001). In Quaternary science, GCMs have been integral components of multi-disciplinary research programmes, early examples of which were the CLIMAP and COHMAP programmes described above. These were important milestones in palaeoclimate research, for they provided the first quantitative expression of the major processes affecting the Earth's climate system, as well as focusing attention on cause and effect mechanisms involving seasonality influences, ocean–atmosphere–cryosphere feedbacks, and lag and response between climate-forcing signals and atmospheric circulation changes (Wright *et al*. 1993). Modelling of the late Quaternary glacial–interglacial cycles has also provided further confirmatory evidence of the role of the Milankovitch variables in long-term climate change (Imbrie & Imbrie 1980).

Numerical modelling has not been confined to GCMs, however, for an array of models has been developed that represent the operation of Earth-surface systems at a range of spatial scales. These vary from hydrological models of changes in water balance within a pluvial lake basin (Kutzbach 1980, and see above), to more complex models such as those that simulate meltwater discharge from glacier-dammed lakes (Alho *et al*. 2005). Particular attention has focused on the modelling of ice sheets and glaciers (Siegert 2001). These models have benefited not only from enhanced computing power, but also from more detailed inputs from satellite imagery and other remotely sensed sources. A greater understanding of glacier physics, ice-sheet dynamics, and Earth rheology has also been a key element in model development. Early steady-state ice-sheet models (Boulton *et al*. 1977; Denton & Hughes 1981) were followed in the 1990s by dynamic simulations of ice-volume variations through a glacial cycle (Bintanja *et al*. 2002). Not only do these provide important new insights into spatial and temporal behaviour of the Quaternary ice masses, they are critical to an understanding of glacial isostatic adjustment processes, and hence are an essential element in understanding late Quaternary sea-level change (see above).

Numerical modelling has also been successfully applied to biological data, where it has been used, *inter alia*, to explain patterns and processes of pollen dispersal (Sugita 1993), to examine tree migration (Collingham *et al*. 1996) and to investigate Pleistocene faunal extinctions (Brook & Bowman 2004). Numerical modelling has also been employed in studies of human migration, such as in the analysis of rates and patterns of human dispersal from Africa (Mithen & Reed 2002). Some of the most important aspects of modelling have involved the relationship between past vegetation and climate; for example, in the reconstruction of continental-scale biomes based on compilations of pollen records, which can then be compared with biomes simulated by GCMs and used to analyse global vegetation–climate dynamics on millennial time scales (Prentice 1998; Williams *et al*. 2000). Equally significant has been the development of highly complex coupled ocean–atmosphere–vegetation models that simulate past climatic variability (Renssen *et al*. 2005). Essential to the success of these experiments are international collaborative programmes, such as the Palaeoclimate Modelling Intercomparison Project (PMIP; Joussaume & Taylor 2000), which aim to establish agreed protocols for model design and development.

The importance of numerical modelling lies not only in reconstructions based on the Quaternary palaeoclimatic and palaeoenvironmental record, but also in the fact that models can be manipulated to evaluate the nature, magnitude and timing of future environmental response. This predictive aspect allows future scenarios to be simulated and assessed. For example, the hypothesis that greenhouse-gas concentrations in the atmosphere may have delayed the onset of the next glaciation (see above) has been tested and confirmed by the GENESIS climate model (Ruddiman *et al*. 2005), and the same model has also been employed to predict mass-balance changes in the Greenland and Antarctic ice sheets following a doubling of atmospheric CO_2 (Thompson & Pollard 1997). It is in modelling exercises such as these that the enormous achievements of Quaternary science over the course of the last 50 years find their most powerful expression. Only now do we have a database of the required level of sophistication to calibrate the increasingly complex models that are required to provide realistic scenarios for future global change, and that are a vital component in the development of a successful strategy for managing our planet (Houghton *et al*. 2001).

The Quaternary and the geological time scale

Despite the long and distinguished history of Quaternary studies, the range and quality of the palaeoenvironmental data that have been generated, and the progress that has been made towards an understanding of the driving mechanisms of Quaternary climate change, the terminology and classification of Quaternary time, its equivalents and its subdivisions, continues to be the subject of debate (Aubry *et al*. 2005; Clague 2005; Walsh 2006). The Quaternary has long been considered to be a geochronological unit of period status and to include two distinct epochs, the Holocene (0–11.5 ka BP) and Pleistocene (pre-11.5 ka BP). For a variety of reasons, however, the position of the Quaternary within the geological time scale has never been formally resolved or ratified by the International Union of Geological Sciences (IUGS), although the lower boundary of the Quaternary has. In the early 1980s, a stratigraphic sequence at Vrica in southern Italy was formally accepted by the IUGS as the type section for the base of the Pleistocene (Aguirre & Pasini 1985), the Pliocene–Pleistocene boundary being placed at the first appearance of a cold-water fauna and palaeomagnetically dated to *c*. 1.64 Ma, subsequently revised to 1.81 Ma (Hilgen 1991).

Over the past 20 years, however, there has been an increasing groundswell of opinion to move the base of the Quaternary back to 2.6 Ma. Between 3.0 and 2.6 Ma, the astronomically forced climatic cycle increased in amplitude and became dominated by the 41 ka obliquity signal (Fig. 4). This change in the Earth's climate system represents the crossing of a key threshold, for it led to global-scale cooling, a major expansion of Northern Hemisphere ice sheets, and the initiation of a pattern of glacial–interglacial cycles that has dominated the world's climate to the present day (Pillans & Naish 2004). This climatic shift also appears to have been of much greater magnitude and importance than the global changes at around 1.8 Ma. The 2.6 Ma transition also coincides closely with the Gauss–Matuyama geomagnetic boundary, and correlates with the bases of marine oxygen isotope stage 103 and the Gelasian Stage of the Neogene system, the uppermost chronostratigraphic stage of the Pliocene. Moreover, it is during the past 2.6 Ma that hominids evolved and began to exert an increasingly influential role on floral and faunal distributions and on the operation of Earth-surface processes. The changes initiated at 2.6 Ma therefore altered the Earth's boundary conditions in a fundamental manner, and hence it is appropriate that this should be reflected in formal geological terminology and classificatory schemes.

A joint task-group of the International Union for Quaternary Research (INQUA) and the International Stratigraphy Commission (ICS) has recently recommended that the Quaternary be formally established using the base of the Gelasian Stage (*c*. 2.6 Ma) of the upper Pliocene Series, and that the Quaternary should be a full formal chronostratigraphic unit of system or period status (e.g Gibbard *et al*. 2005; Bowen & Gibbard 2007). The Executive Committee of the IUGS has accepted the latter definition, but has indicated that there should be further discussion on the base of the Quaternary at the International Geological Congress in Oslo in 2008. In due course, however, it is hoped that both task-group recommendations will be accepted and ratified by the IUGS, and that the Quaternary, as so defined, will be incorporated into the new geological time scale.

The Quaternary community and the challenge of the future

In the 50 years that have elapsed since the publication of R.F. Flint's *Glacial and Pleistocene Geology*, the pace of scientific discovery has been truly remarkable, and our perspective on the nature of global environmental change has been radically transformed. The Quaternary stratigraphic record, perhaps more than any other in the geological column, provides the most striking example of the interdependence between terrestrial, marine, cryospheric, biospheric and atmospheric systems and processes. Indeed, Quaternary scientists were among the first to appreciate and espouse the principles of Earth-system science, the notion that all Earth components and processes are inextricably linked. Effective study of any one of the subsystems that make up the total global environment requires an appreciation of the synergistic links that it has with all of the others (Ernst 2000;

Mackenzie 2002). In many areas of the natural sciences, increasing specialization has tended to encourage a narrowing of focus and vision. Most Quaternary scientists, however, are familiar and comfortable with complex, multi-proxy investigations in which diverse lines of sedimentary, biological or chemical evidence are combined to produce an integrated narrative of past environmental or climatic changes.

It is this inter- or multi-disciplinary approach that has been an increasing characteristic of Quaternary research over the past 50 years, and that has enabled (and continues to enable) Quaternary science to make a major contribution to the understanding of the history of this planet. In the wider context of geological research, however, there are two aspects of the Quaternary that set it apart from other time intervals. First is the high degree of temporal resolution at which the Quaternary record can be interrogated, and with further refinements in geochronology, reconstructions of past global climatic and environmental change at a decadal to annual scale may become almost routine. The second is that, as noted above, the Quaternary record provides the best historical analogues for evaluating the manner and scale of adjustment of the contemporary global environmental system to future change. The challenge for Quaternary scientists over the next 50 years, therefore, is to generate integrated datasets of the highest possible quality and temporal resolution to provide meaningful baselines for predictive models of the global future.

In many ways, however, perhaps the most important development in Quaternary science over the past five decades has been the evolution of a large international, inter-disciplinary community of like-minded scientists who share a common goal in unravelling the past 2.6 Ma of Earth history. The International Quaternary Union (INQUA), founded in 1928, has more than 30 member countries from all five continents, holds an annual congress every 4 years and sponsors, through its various Commissions and Working Groups, research activity across the entire spectrum of Quaternary science. INQUA's active members, include anthropologists, archaeologists, biologists, chemists, climatologists, computer scientists, geochemists, geographers, geologists, geomorphologists, mathematicians, oceanographers, palaeontologists, physicists and statisticians, often working on common projects. Many countries have their own dedicated Quaternary research organizations, which foster inter-disciplinary research; these include the Association Française pour l'Etude du Quaternaire (AFEQ) in France (founded 1962), the Deutsche Quartärvereinigung (DEUQUA) in Germany (1964), the Quaternary Research Association (QRA) in Britain (1968), and the American Quaternary Union (AMQUA) in North America (1970). A further indicator of the success of Quaternary science over recent years is the publication record. In the 1950s, there were no scientific journals specifically devoted to the Quaternary. Over the last 30 years or so, six international Quaternary periodicals have appeared: *Quaternary Research* (first issue 1971), *Boreas* (1972), *Quaternary Science Reviews* (1982), *Journal of Quaternary Science* (1985), *Quaternary International* (1989) and *The Holocene* (1991), and many other journals (e.g. *Palaeogeography, Palaeoecology, Palaeoclimatology*; *Paleoceanography*; *Geology*) routinely publish papers with a Quaternary focus. What is more, a growing number of textbooks are entirely devoted to the study of the Quaternary and a comprehensive four-volume *Encyclopaedia of Quaternary Science* (Elias 2006) has recently appeared. Quaternary science is therefore in excellent health, and is well placed to meet the intellectual challenges of the next 50 years. One imagines that, were he alive today, Richard Foster Flint would readily concur!

Dedication

This paper is dedicated to the memory of Professor David Keen, whose untimely death in April 2006 deprived the British Quaternary community not only of a very fine scientist, but of a respected colleague and friend.

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