Quaternary Geography and the Human Past

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Chapter 13

Quaternary Geography and the Human Past

Jamie Woodward

A New Quaternary Geography

Research published in the 1990s reshaped fundamental ideas about Quaternary geography and the tempo of global environmental change. Data from the Greenland ice cores and from North Atlantic marine sediments show that the last cold stage was punctuated by a remarkable series of abrupt and high-amplitude changes in climate and oceanographic conditions (Bond *et al.*, 1993; Dansgaard *et al.*, 1993). These discoveries are driving a new research agenda focused on the causal mechanisms and how ecosystems and geomorphological processes on the surrounding continents reacted to such rapid and repeated oscillations in Quaternary climate (Fuller *et al.*, 1998; Allen *et al.*, 1999; Walker and Lowe, 2007). Some researchers have returned to previously well-studied sites to scrutinise records at much higher resolution in order to examine the sensitivity and response of terrestrial environments during this period (e.g., Tzedakis *et al.*, 2002). It is now clear that these findings have major ramifications for all components of Physical Geography – for geomorphology, biogeography and climatology and how we conceptualise the interactions between them. These findings have also led to new research questions and new approaches in the study of human-environment interactions during the Quaternary Period; especially the Palaeolithic archaeology of the last cold stage (Woodward and Goldberg, 2001; Gamble *et al.*, 2004; Mellars, 2006; Tzedakis *et al.*, 2007).

Much earlier in the 20th century, in the absence of reliable stratigraphic frameworks for both the Quaternary and archaeological records, it proved difficult to tackle even very basic questions about the nature of the relationship between Quaternary environmental change and the human past. Peake (1922, p. 6), for example, outlined some of the central issues at this time:

The problem before us is twofold. Firstly we have to consider whether there was one ice age or several, and in the latter case how many we must account for. The other question, upon which opinion is rapidly hardening, is the relation of the different Palaeolithic periods to the glacial phases.

Quaternary research has always been a meeting place for geographers, geoscientists and archaeologists. These disciplines have long been fascinated by the pace, amplitude and drivers of environmental change, by the nature of ice age ecosystems and by the challenges presented to early human societies by a changing Quaternary geography. It is the emergence of new and more finely resolved windows into the past – as well as improvements in dating methods for both geological and archaeological records – that have, in recent decades, radically transformed the way we think about Quaternary environments, landscape change and past human activity. There is now abundant evidence for rapid and repeated reorganisations of Quaternary ecosystems over centennial to millennial timescales and these would have impacted significantly upon resource availability and human subsistence strategies (see Mithen, 1999).

It is against this background of a newly energised Quaternary geography that this chapter aims to explore some of the practical and theoretical issues associated with locating the Palaeolithic archaeology of the last glacial stage within a precise environmental framework. This is a key research goal despite the traditional tensions within archaeology between ‘environmentalist’ and ‘internalist’ theories. The former emphasise ecological relationships and the determining or limiting effect of basic biological and environmental factors, while the latter derive their main inspiration from the social sciences and emphasise what they call the inherent dynamic of social relations (Bailey, 1983). In this context, Mithen (1999, p. 478) has set out a robust defence of the study of long-term human-environment interactions:

People are not detached from natural environments but are part of them; the natural environment provides opportunities and constraints on human behaviour, and it is in turn changed by that behaviour. When human-environment interactions can be studied over the longer term, it is possible to explore how people adapted to environmental change and this provides us with basic information about the nature of the human condition.

Bailey (1983) and Mithen (1999) argue that these approaches need not be in conflict and, in any case, it can be argued that we need to establish the environmental context of the archaeological period under discussion before that debate can begin. This chapter is not advocating a purely deterministic approach to the investigation of human activity in Late Pleistocene environments. Rather, by recognising the new and exciting opportunities presented by recent advances in Quaternary science, it seeks to explore how we may define new questions and test existing ideas about human-environment interactions in light of the reality of a highly dynamic Quaternary geography and the developing potential for improved dating frameworks. Dating control is a key theme throughout this chapter. Without reliable dating frameworks, it is not possible to establish the pace of environmental change or to compare records – both environmental and cultural – from different contexts.

A good deal of the material covered here builds directly upon the pioneering contributions of Nick Shackleton and Willard Libby (figure 13.1) who revolutionised approaches to the Quaternary record through, respectively, the study of the oxygen isotope record in deep sea sediments (Shackleton, 1967; Shackleton and Opdyke, 1973) and the development of radiocarbon dating (Libby, 1955).

Figure 13.1 Nick Shackleton (1937 to 2006) and Willard Libby (1908 to 1980) are arguably the two most influential figures in Quaternary science in the second half of the 20th century. Nick Shackleton is shown picking forams for oxygen isotope analysis in the Godwin Laboratory in Cambridge (University of Cambridge Newsletter, December 2004). Willard Libby is shown in his Laboratory at UCLA in 1968 (University of California history digital archives).

The Upper Palaeolithic Revolution

Advances in radiocarbon dating are an important part of this story because, as far as the archaeological record of the Upper Palaeolithic is concerned, this is the main method for dating this period and for building correlations between archaeological sites over the past 50,000 years or so (Mellars, 2006). This is a small portion of Quaternary time, but it incorporates dramatic changes in both the environmental and archaeological records. It is a key period in human history that saw the demise of the Neanderthals (the end of the Middle Palaeolithic) and the establishment of anatomically modern humans (Cro-Magnons) as the sole human species. In Europe this is known as the Upper Palaeolithic revolution (Mellars, 1994).

The Upper Palaeolithic is marked by a set of fundamental cultural shifts that set it apart from the Middle Palaeolithic. Stone tool production shows greater innovation and a much wider range of tool types. New raw materials enter the human tool kit – with elaborate use of bone and antler – and this period saw the development of more effective social networks (Gamble 1986; 1999). Perhaps the most striking aspect of the Upper Palaeolithic record in Europe are the remarkable cave paintings of France and Cantabrian Spain from sites such as Lascaux, Chauvet and Altamira (Bahn and Vertut, 1997) (figure 13.2). Questions surrounding the causes (whether environmental or cultural, or a combination of both) and precise timing of the Neanderthal extinction, and the pace of modern human (Cro-Magnon)

Figure 13.2 Upper Palaeolithic cave paintings from Chauvet Cave in southern France. The upper image shows a pride of lions and the lower image shows a rhino from a group of seventeen in Chauvet Cave. Both photographs by Jean Clottes and reproduced with permission from the French Ministry of Culture and Communication (Direction régionale des affaires culturelles Rhône-Alpes). AMS radiocarbon dating has allowed the pigments and charcoal from such images to be dated directly and this can provide valuable insights into the nature of ice age ecosystems. Upper Palaeolithic art in Europe has a very distinctive geography – it is mainly concentrated in the Dordogne, Cantabrian Spain and the Rhone Valley.

dispersal across Europe, have generated much debate (Stringer and Gamble, 1993). A key area of controversy is the interpretation of radiocarbon dates because many of these cultural changes took place towards the practical upper limit of this dating method (Mellars, 2006).

To explore some of the problems involved in charting the interactions between environmental change and human activity over the course of the last cold stage, this chapter will focus upon examples from Western Europe and the Mediterranean within the period between c. 50,000 and 10,000 years ago. We now know that this period includes Heinrich Events 1 to 5 when massive discharges of icebergs from the Laurentide Ice Sheet chilled the surface of the North Atlantic and created a bitterly cold and dry climate across the surrounding land masses. This period also includes the global Last Glacial Maximum (c. 20–22 ka) when the major continental ice sheets in North America and Eurasia reached their maximum extent. To understand the full significance of the data obtained from the North Atlantic marine sediment record and the Greenland ice cores, it is instructive to consider some early ideas about the glacial record and the first major paradigm shift in Quaternary science that took place in the 1970s.

The Alpine Model of Quaternary Glaciation

In the late 19th and early 20th centuries, much effort was centred on establishing the number of Quaternary glaciations and the antiquity of humans (Peake, 1922 and see Grayson, 1990; Gamble, 1994). This period saw some of the earliest interaction between geologists and archaeologists (Goudie, 1976). For much of the 20th century, the glacial record of the Quaternary was synonymous with the framework put forward by Albrecht Penck and Eduard Brückner published in 1909 and this model gained widespread support after the First World War (see Peake, 1922; Bowen, 1978). This scheme was based on geomorphological fieldwork in the northern forelands of the Alps where they recognised a series of glacial and fluvial landforms (primarily moraines and river terraces) and associated sediments representing four main periods of Quaternary glaciation (table 13.1). These glacial periods were named Gunz, Mindel, Riss and Würm after the river valleys that contained these deposits. The Alpine scheme is based on a discontinuous terrestrial record that

Table 13.1 Penck and Brückner's (1909) model of four major Quaternary glaciations and interglacials (based on table 2.1 in Bowen, 1978). The values on the right are estimates of the length of the interglacials relative to the post-glacial (Holocene) period. The Mindel-Riss interglacial became known as the Great Interglacial

<i>Stage</i>	<i>Landform or process</i>	
<i>Post-Würm (Holocene) interglacial</i>	<i>incision</i>	1
Würm Glaciation	Niedterrassen (Low Terrace)	
<i>Riss-Würm interglacial</i>	<i>incision</i>	3
Riss Glaciation	Hochterrassen (High Terrace)	
<i>Mindel-Riss interglacial</i>	<i>incision</i>	12
Mindel Glaciation	Younger Deckenschotter	
<i>Günz-Mindel interglacial</i>	<i>incision</i>	3
Günz Glaciation	Older Deckenschotter	

contains large gaps. The interglacial periods, for example, are represented, not by sediments, but by long phases of incision in the river valleys (table 13.1). A key weakness of this model was the lack of a reliable time frame for the events it represented (Bowen, 1978) although Penck and Brückner (1909) did provide estimates for the length of the interglacial periods relative to the Holocene or post-glacial period (table 13.1). This framework became a cornerstone of Quaternary research and records from around the world were correlated with the Alpine model (see Bowen, 1978 for a detailed discussion).

The Marine Realm: Oxygen Isotopes and the Glacial Record

The Penck and Brückner model persisted for so long partly because there were no convincing alternatives and partly because it could not be challenged effectively in the absence of reliable dating frameworks for long records of change. This situation changed in the 1960s and 1970s as attention shifted to the study of the continuous Quaternary records in the deep ocean basins and the use of oxygen isotope analysis.

Oxygen has three stable isotopes (^{16}O , ^{17}O and ^{18}O) and because the lighter isotope evaporates more easily, atmospheric water vapour contains more ^{16}O and less ^{18}O than the parent sea water. This process is called fractionation and it means that continental ice sheets and glaciers are enriched in ^{16}O and, as ice sheets grow, the oceans become relatively enriched in the heavier isotope ^{18}O . The oxygen isotope ratio of ocean water is recorded in the calcium carbonate shells of tiny organisms called forams. When they die they form part of the marine sediment record. These simple creatures and these physical principles were the key to unlocking the glacial record of the Quaternary.

Some species of forams produce shells with a composition that is in isotopic equilibrium with the water that they inhabit and the oxygen isotopes can be measured using a mass spectrometer. This means that a long core of foram-rich marine sediment can provide a record of long-term shifts in the isotopic composition of the oceans. A cold stage or glacial ocean is enriched in the heavier isotope (^{18}O) because huge amounts of ^{16}O are locked within the continental ice sheets. Conversely, a warm stage or interglacial ocean contains more of the lighter isotope (^{16}O) because ice sheet melting returns ^{16}O to the oceans. Shackleton (1967) had already shown that the oxygen isotope record from Quaternary marine sediments was primarily a record of changes in global ice volume and not a record of changes in ocean temperature as had been argued previously (Emiliani, 1955). Thus, oxygen isotope measurements can provide valuable insights into long-term changes in the global hydrological cycle.

Shackleton and Opdyke (1973) worked on a 16-m sediment core (V28–238) recovered from the Solomon Plateau on the floor of the equatorial Pacific and measured the oxygen isotope ratio of foram samples for the entire length of the core. Their oxygen isotope curve is shown in figure 13.3. The troughs in this curve mark those periods when global ice volume reached its maximum extent during glacial stages and these are marked with even numbers. The odd numbers represent interglacial periods when global ice volume was much reduced and eustatic sea level was high. These are commonly referred to as marine isotope stages (MIS) and MIS 5, for example, is the last interglacial.

This record revolutionised the study of the Quaternary because Shackleton and Opdyke (1973) were the first to set an oxygen isotope curve (and the long-

Figure 13.3 The oxygen isotope record from ocean core V28–238 modified from Shackleton and Opdyke (1973). The Brunhes-Matuyama magnetic reversal coincides with Marine Isotope Stage 19 and this event provided the basis for estimating the age of the glacial and interglacial stages shown in this core. Shackleton and Opdyke used a value of 730 ka for this event, but this was later refined to 780 ka in the light of more recent data. Note the rapid transition from cold stages to warm stages – these are known as Terminations as shown on figure 13.5. The global Last Glacial Maximum corresponds to MIS 2 and the post-glacial or Holocene period corresponds to MIS 1.

term record of continental glaciation it represented) within a robust dating framework. To achieve this they utilised long-term changes in the Earth's magnetic field.

Marine isotope stage 19 in core V28–238 coincides with the Bruhnes-Matuyama magnetic reversal, the last time that the Earth's magnetic field flipped. All of the sediments above MIS 19 have normal polarity. The age of this reversal event was known and it allowed a timescale to be developed for the entire record based on the reasonable assumption of a constant rate of sedimentation for deep ocean sediments. The ages of all sections of the core were interpolated from this datum. This showed that the Bruhnes Epoch alone contained eight full glacial-interglacial cycles (figure 13.3) and this accounted for much less than half of Quaternary time. In contrast, the Penck and Brückner model had just four for the entire two million years or so of the Quaternary Period (table 13.1).

The continuous record of glacial and interglacial cycles from core V28–238 had a profound impact on Quaternary science and it provided a yardstick against which all other records could be evaluated. At the end of the decade, Bowen published a paper in *Progress in Physical Geography* entitled 'Geographical Perspective on the Quaternary' that drew much of its inspiration from the V28–238 record. It began with the following statement (Bowen, 1979, p. 167):

A revolution has taken place in Quaternary research that is in effect comparable to that of plate tectonic theory in the geological sciences as a whole. Its implications

extend deep into the fundamental methodological foundations of all geographical sciences concerned with matters related to the past. It relates predominantly to a change in scale and complexity which, although hinted at earlier this century, could hardly have been imagined at the opening of the post-World War II period.

As Bowen argued so forcefully, the oxygen isotope record from the marine archive had major implications for all components of Quaternary geography – it made geomorphologists, glaciologists and ecologists rethink the tempo of Quaternary landscape and vegetation dynamics – it also led to new ideas in human evolution and adaptation (Gamble, 1986). In short, this work forced a radical rethink about the complexity and dynamics of Earth system change during the course of the Quaternary Period and it signalled the end of the Alpine framework. The record was soon replicated in all the major marine basins and a series of marine oxygen isotope records were later used by Shackleton and co-workers to show that the rhythms of the ice ages were controlled by astronomical parameters as predicted by Milankovitch much earlier in the century (Hays et al., 1976; Imbrie and Imbrie, 1979).

Dating the Terrestrial Records: The Radiocarbon Method

Radiocarbon dating was developed by Willard Libby and his team at the University of Chicago in the years immediately after the Second World War. Libby was awarded The Nobel Prize for Chemistry in 1960 ‘for his method to use carbon-14 for age determination in archaeology, geology, geophysics, and other branches of science’. Radiocarbon (^{14}C) is continually produced in the upper atmosphere and it enters all living organisms via the carbon dioxide cycle. On the death of a plant or animal, the uptake of radiocarbon ceases and the radiocarbon store in the organism continues to decay, but without replenishment. So death sets the radiocarbon dating clock ticking so that with a few assumptions, it is possible to establish the amount of residual radioactivity per gram of carbon in a fossil sample and, using modern standards and the measured half-life of radiocarbon ($5,730 \pm 30$ years), it becomes possible to calculate a date for the death of the sample (Libby, 1955; Bowman, 1990).

The measurement of radiocarbon requires sensitive and specialist laboratory equipment because for every one million million atoms of stable carbon (^{12}C) in a living organism, there is just a single atom of ^{14}C (Lowe and Walker, 1997). The sensitivity of the method has been significantly enhanced through the use of Accelerator Mass Spectrometry (AMS) as this allows ^{14}C atoms to be detected and counted directly in contrast to conventional dating which only detects those atoms that decay during the time interval allotted for an analysis. AMS offers several advantages because the measurement time is much quicker and only very small samples of carbon (1 mg or less compared to 5 to 10 g for conventional dating) are needed for dating (Gowlett et al., 1997; Bell and Walker, 2005). AMS represented a key breakthrough for studies of the Middle and Upper Palaeolithic because it allowed small samples of charcoal to be dated instead of bone samples – the latter are susceptible to contamination by more recent carbon from percolating groundwater. This process can top up the amount of residual radiocarbon in a bone sample to give a spuriously young age.

Another recent breakthrough has seen the application of the AMS approach to obtain radiocarbon determinations directly from cave paintings by dating small samples of the pigments and fragments of charcoal that form the images on the cave walls (e.g., Valladas, 2003) (figure 13.2). Previously, the chronology of the cave

paintings was loosely based on the style of the images. This work offers the potential to provide a much more rigorous basis for the development of a detailed chronology of Upper Palaeolithic art across Europe, but some of the AMS results and their interpretation have been contested (Pettitt and Bahn, 2003).

A key assumption of the method is that the ratio of radiocarbon (^{14}C) to stable carbon (^{12}C) has remained constant in the Earth's atmosphere so that the measurement of residual radiocarbon in a given sample provides a reliable indication of its true age. However, it is now well established that radiocarbon production in the upper atmosphere has fluctuated markedly during the Quaternary (see Bard et al., 1990; Mellars, 2006) and radiocarbon dates therefore have to be calibrated because radiocarbon years are not directly equivalent to calendar years. In theory, radiocarbon dating can be used to date organic materials up to 50,000 years old, but in practice many researchers do not place much faith in dates older than about 40,000 years because the ages can be distorted by sample contamination. Furthermore, the development of calibration curves and algorithms for such old samples is still in its infancy.

Since the radiocarbon method was pioneered by Libby in the 1940s, it has seen a series of fundamental changes in the measurement and interpretation of results. The key changes are largely responses to the problems associated with age calibration and sample contamination, and these factors are especially acute for radiocarbon determinations beyond six half-lives. However, in a stimulating and sanguine review, Mellars (2006) argues that recent methodological advances have dramatically reduced both of these sources of error. First, new pretreatments for the purification of bone collagen have effectively removed the problem of contamination by more recent carbon. Second, a new calibration model based on data from various sites around the world now provides the best available means of calibrating radiocarbon dates over the last 50,000 years (e.g., Hughen et al., 2004). This calibration shows that a radiocarbon date of 35,000 years BP is equivalent to a calendar age of approximately 40,500 years BP. It is therefore of crucial importance when reporting dating results to make a clear distinction between radiocarbon years and calendar years. The systematic displacement of radiocarbon ages from true calendrical ages has very clear implications for any comparison between radiocarbon-based chronologies from archaeological sites and proxy climate records such as the Greenland ice cores or other geological archives that have been dated by other methods (Woodward, 2003; Mellars, 2006). If the purification of bone samples and calibration back to 50,000 BP become routine over the next few years, this will present exciting opportunities to test ideas about the nature of the Middle to Upper Palaeolithic transition. Mellars (2006) has already begun to put forward a case for a much more rapid transition and a more rapid dispersal of modern humans across Europe.

Quaternary Geography: Transects Across Europe

Figure 13.4 shows transects across Europe from the Mediterranean Sea to the Arctic Ocean under interglacial and glacial conditions. Each transect shows, in broad terms, the major ecosystems present across the continent at the extremes of warm and cold stages – the odd and even numbered stages, respectively, on figure 13.3. The cold stage geography of Europe shows a large mid-latitude ice sheet fringed by a belt of polar desert and steppe tundra. It shows a few trees on the southern slopes

Figure 13.4 Transects across Europe from south to north showing schematic representations of the vegetation belts associated with glacial and interglacial stages (modified from van der Hammen et al., 1971). We know from the long pollen records in the Mediterranean that trees survived in the south throughout the Pleistocene. Without the presence of long-term refugia in the south, northern tree populations could not be re-established during interglacials.

of the Alps and the Mediterranean region is shown as a steppe environment. Each ecosystem would have supported a range of fauna including large herbivores such as mammoths, reindeer and horses, and each presented a range of opportunities and challenges for human societies (Gamble, 1986). These and other fauna have been recorded from the bone assemblages recovered from the excavation of Middle and Upper Palaeolithic sites across the region. These animals are also represented in the cave paintings of France and northern Spain where the galleries provide wonderful insights into the geography of ice age Europe and showcase the creativity and skill of Upper Palaeolithic human groups (Figure 13.2). The cold stage geography of Europe will be discussed in more detail below.

The Quiet Revolution: Rapid Climate Change

Shackleton continued to work on much longer cores throughout the 1970s and 1980s and he extended the oxygen isotope record back for the entire Quaternary and deep into pre-Quaternary time. This work provided the first indications of a Quaternary geography that was far more dynamic than anyone had previously contemplated. Figure 13.5 shows four long proxy climate records. Figure 13.5a is an oxygen isotope curve for the entire Quaternary from ODP Site 677. This is a much longer record than the one from core V28–238 shown in figure 13.3 as it shows changes in global ice volume over the last 2.5 million years. This remarkable pattern of environmental change was compiled by Shackleton and Crowhurst (1996) and it includes several magnetic reversals back to MIS 104. There is an important step change around 900,000 years BP (MIS 22) known as the mid-Pleistocene Revo-

Figure 13.5 (a) The long oxygen isotope record from ODP Site 677 in the tropical Pacific Ocean showing changes in global ice volume and shifts from glacial to interglacial conditions for the entire Quaternary Period. Note that this record extends back beyond 2.5 million years and the record contains several magnetic reversals. Compare to figure 13.3. Roman numerals mark Terminations I to XI (modified from Shackleton and Crowhurst 1996). (b) The marine oxygen isotope record for the last 250,000 years in more detail showing the subdivisions within the interglacials of MIS 5 and MIS 7. The terms used by Gamble (1994) for the Palaeolithic occupation of Europe are also shown. Towards the end of MIS 3 the Neanderthals (Ancients) were replaced by Cro-Magnons (Moderns). (c) Abrupt changes in temperature from 60 to 10 ka shown in a high-resolution ice core record from Greenland (after Dansgaard et al., 1993). (d) The record of ice-rafted debris (IRD) from marine sediments in the North Atlantic between 60 and 10 ka. These discrete layers of coarse material mark the Heinrich Events of the last cold stage (modified from Roucoux et al., 2005 and sources therein).

lution when the glacial cycles change to a dominant 100,000-year cycle and there is a much larger contrast in ice volume between cold and warm stages.

The next curve (figure 13.5b) shows the last 250,000 years in more detail along with the terms from Gamble (1994) for the human occupation of Europe in the Palaeolithic. The Ancients are the Neanderthals and the Pioneers are the final Neanderthal groups who disappeared from the archaeological record in Europe in MIS 3. Figure 13.4 showing the transects across Europe discussed above was published in 1971 and it can be argued that it reflects a more general tendency for some Quaternary researchers to focus on the palaeogeography at the *extremes* of glacial and interglacial conditions. To some extent the oxygen isotope records reinforced this view as Porter (1989, p. 245) has argued:

In Quaternary research, it is all too easy to view the glacial ages simplistically as a succession of glacial and interglacial culminations during which the extent and volume of glacier ice were at a maximum or minimum.

In reality, and this is shown very clearly by the marine oxygen isotope records (figures 13.3 and 13.5a,b), conditions during the Quaternary Period were, for much of the time, *intermediate* between these extremes and, after all, the peaks of glacial and interglacial periods were relatively short-lived. Porter (1989) argued that this was an important consideration when examining geomorphological and ecological processes during the Quaternary Period. It is clear, however, that for much of the Quaternary, global ice volume was much greater than present-day values. Figure 13.5b shows a relatively slow build-up of continental ice during the course of marine isotope stages 2 and 6 with extended periods of very harsh conditions ending in a brief period of rapid ice sheet melting known as a Termination. However, the high-resolution data from the North Atlantic and from the Greenland ice cores have dispelled any notions of long-term ice sheet stability and glacial monotony as is shown in figure 13.5c,d. One of the most remarkable discoveries of the 1990s was that the last cold stage was punctuated by centennial- to millennial-scale variations in climate and these are clearly recorded in the ice core records (figure 13.5c) with significant fluctuations in air temperatures in Greenland throughout this period. These are known as Dansgaard-Oeschger cycles and they represent air temperature shifts of the order of 15°C (Dansgaard et al., 1993).

Another key discovery of the last two decades was the presence of ice-rafted debris in the marine sediment record across the North Atlantic (figure 13.5d). These sediments show that the North American (Laurentide) ice sheet was highly dynamic throughout the last cold stage as large discharges of icebergs periodically flowed out across the North Atlantic and cooled the ocean surface. These are known as Heinrich Events and their impact on the climate system has been recorded in a variety of proxy records across the European continent (Bell and Walker, 2005; Anderson et al., 2007). As the drifting ice melted, it lowered the salinity of surface waters and this is clearly recorded in the oxygen isotope signal from foram species that lived in the upper part of the water column (Bond et al., 1993). The recognition of Heinrich Events showed the potential scale and rapidity of cryosphere-ocean-atmosphere interactions during the last cold stage.

For the second time within two decades, revelations from the marine record have forced Quaternary scientists to revise their ideas about long-term ice sheet dynamics and the drivers of environmental change, and to ask new questions of the terrestrial records. Indeed, the extract from Bowen (1979) cited above is just as relevant almost 30 years on as the combined impact of these findings alongside the Greenland ice core records has been profound across both the Quaternary science and archaeological communities. A direct result of these revelations is that most research is now done at much higher resolution than before, with more finely resolved sampling and better dating control. The impact of these changes for the study of long-term human-environment interactions will be discussed below.

A Mediterranean Perspective: High-Resolution Records

Another important development in European Quaternary research in the last two decades has seen a significant increase in the volume of work conducted south of

the Alps in the Mediterranean region. There are good reasons for this. It can be argued that the Mediterranean has the best set of long-term terrestrial Quaternary records in Europe if not the rest of the world (Woodward, 2009). The region contains distinctive tectonic settings with long-term sediment sinks spanning multiple glacial-interglacial cycles and, in some cases, all of the Quaternary. The long lake sediment records, for example, can be compared directly with the marine archive (Tzedakis et al., 1997) and because the region lay south of the major European ice sheets, many of these sedimentary records are continuous and well preserved. An added advantage is the fact that the geology of the region offers many opportunities for dating and often at better resolution than in other parts of Europe. The widespread occurrence of limestone, for example, has produced karstic features and secondary carbonates that can be dated using uranium-series methods and this has produced new insights into the glacial records for example (Woodward et al., 2004; Hughes et al., 2006). The presence of explosive volcanic centres has spread volcanic ash (tephra) over wide areas (Narcisi and Vezzoli, 1999; Wulf et al., 2004) and this material can be dated directly. Tephra can be used to correlate between records that are many hundreds of kilometres apart and they have even been found in Upper Palaeolithic rockshelter sediment records in Greece (Farrand, 2000) and Montenegro (Brunnacker, 1966).

Parts of the Mediterranean region formed important refugia for tree species during cold stages of the Pleistocene. When climate ameliorated and trees were able to expand their ranges from refugial centres, the long pollen records show that they were able to do this very rapidly (figure 13.6). In contrast to areas much further to the north, this created a much more dynamic Pleistocene geography. Allen et al. (1999) have examined the long lake sediment record from Lago Grande di Monticchio in southern Italy. This record covers the last 102,000 years and it shows a series of rapid environmental changes during the last cold stage that correlate well with the Greenland ice core records. This is a sensitive, high-resolution record that allows centennial to millennial scale climate variability to be examined. Rapid vegetation changes took place in this region during the last cold stage over timescales of less than 200 years. This a key terrestrial archive of environmental change in southern Europe for the last glacial cycle. Allen et al. (1999) show very clearly that the terrestrial biosphere was a full participant in these rapid fluctuations and they conclude that:

the closely coupled ocean-atmosphere system of the Northern Hemisphere during the last glacial extended its influence at least as far as the central Mediterranean region

The marine sedimentary record in the Mediterranean is also a very distinctive archive of environmental change that is linked directly to the North Atlantic via water exchange at the Straits of Gibraltar. The Mediterranean Sea is a relatively small body of water in the global ocean system, but it is very sensitive to environmental change and the high sedimentation rates in the basin form excellent records of change (Cacho et al., 1999). It is now well established that the impact of Heinrich Events is clearly recorded in the western Mediterranean basin because cold North Atlantic waters entered the basin via the Straits of Gibraltar and the regional climate became cooler and drier during these periods. Figure 13.6a shows two parameters from the marine archive in the western Mediterranean that record the impact of Heinrich Events very clearly. These cooling and drying episodes placed great stresses on terrestrial ecosystems and the pollen records from several sites in the Mediterranean show that tree cover contracted rapidly during these periods. Three long pollen records from basins in contrasting settings in Greece are shown in figure

Figure 13.6 High-resolution marine and terrestrial records from the Mediterranean basin between c. 50 and 10 ka (see figure 13.5). The upper figure (a) shows the marine record from core MD95–2043 in the Alboran Sea showing discrete cooling events in the western Mediterranean Sea in response to Heinrich Events in the North Atlantic (modified after Cacho et al., 1999). The lower figure (b) shows the response of the temperate tree populations at three sites in Greece (table 13.2). See text for discussion (modified from Tzedakis et al., 2004).

13.6b and the impact of Heinrich Event 4 is especially clear at Ioannina and Kopais (table 13.2). A key challenge is to establish the impact of Heinrich Events on resource availability and human survival strategies at these times.

In the same kinds of deep limestone caves that contain the ice age art mentioned earlier, important high-resolution records of climate change have been recovered from speleothems in the Mediterranean region (figure 13.7). Speleothems are the product of calcium carbonate precipitation from groundwater. This process takes place very slowly over long periods of time and they record the changing oxygen isotopic composition of the groundwater. Speleothems can be dated using the uranium-series method and this provides a robust chronological framework. These caverns and their hydrology are also sensitive environmental systems and they have recorded the impact of Heinrich Events, for example, in the most easterly parts of the Mediterranean region over 4,000 km from the North Atlantic Ocean. An example from Soreq Cave in Israel is shown in figure 13.7. It shows marine isotope stages 1 to 6 with evidence of rapid environmental change within MIS 5 as well as rapid and high-amplitude change between 50,000 and 10,000 years BP. This record is important because it shows that the Heinrich Events in the North Atlantic

Table 13.2 Geographical attributes for three long pollen records in Greece (modified after Tzedakis et al., 2004). Ioannina is west of the Pindus Mountains and is the highest site with much higher rainfall than both Kopais and Tenaghi Philippon. Kopais is the driest site with higher summer and winter temperatures and greater losses of moisture to evaporation. Tenaghi Philippon is the most northerly location and is prone to incursions of cold continental air masses from the north and east. These topographic and meteorological factors combine to create limiting factors for tree growth in the drier parts of Greece to the east of the Pindus Mountains divide

Site	Latitude and Longitude	Elevation	MAP	T_{jan}
Tenaghi Philippon	41°10'N and 24°20'E	40 m	600 mm	3.4°C
Ioannina	39°45'N and 20°51'E	470 m	1200 mm	4.6°C
Kopais	38°26'N and 23°03'E	95 m	470 mm	9.0°C

Figure 13.7 Speleothems and palaeoclimate data from speleothem records in the Mediterranean. The photograph shows speleothems from Campanet Cave in Mallorca. The diagram shows an oxygen isotope curve from speleothems in Soreq Cave in Israel based on the work of Bar-Matthews et al. (2000). The record shown here goes back to MIS 6 and evidence for rapid climate change is especially clear in marine isotope stages 5, 3 and 2 (modified after Bar-Matthews et al., 2000).

impacted on climatic conditions across the entire Mediterranean region (Bar Matthews et al., 1999) and it also shows that some were felt more strongly than others. Such proxy climate records from the Mediterranean are important because the region contains many Middle and Upper Palaeolithic sites and the region formed a refuge for humans during the last cold stage.

Environmental Archives: Resolution and Sensitivity

All Quaternary archives of change that provide us with insights into past environments and processes can usefully be assessed and compared in terms of their tem-

poral resolution and their sensitivity to environmental change (Lewin, 1980; Allen et al., 1999; Woodward and Goldberg, 2001). One approach is illustrated in figure 13.8. Temporal resolution is a measure of the completeness and precision of the stratigraphic record at a given site – or within a particular sequence – and the dating control available for that record. A sequence with many erosional gaps and few dates would constitute a low resolution record and this would provide only a very limited window into the past. In contrast, however, some depositional environments involve more or less continuous sedimentation and this provides a sound basis for the development of a reliable and consistent record of environmental change, especially where sedimentation rates are high and the preservation of pollen and other proxies is good. These tend to be low energy settings such as lake and marine environments where sub-aerial erosion is absent and sediments can accumulate, undisturbed, for an extended period of time.

Environmental sensitivity is less easy to quantify, but it is a useful concept and a key characteristic of any environmental system (such as a lake or marine basin, a cave or river catchment system) that produces a long-term record of environmental change (see Wright, 1984). This property relates to the archive's ability to respond to and record an environmental change. Its sensitivity may determine whether it records local, regional or global signals in a consistent and predictable way.

Figure 13.8 shows that lake sediments and speleothems can provide well-dated, high-resolution records of change and these are typically associated with systems that are sensitive to change – they are commonly responsive to external climate fluctuations and they record them in a reliable and consistent manner. This sensitivity can be tested by contemporary process studies (Bar Matthews et al., 1999). Some lake systems accumulate sediments with annual laminations that can be counted. These contexts provide a basis for the development of extremely robust and detailed chronologies and they can be used to test the integrity of other dating methods (e.g. Allen et al., 1999). In contrast, coarse-grained clastic cave sediments (such as the ones shown in figure 13.9) plot at the opposite end of this continuum. These are angular scree sediments that can be produced by a range of mechanisms including frost action or even seismic shaking (Bailey and Woodward, 1997).

A key point to make here is that much of the Middle and Upper Palaeolithic record in Europe has been recovered from coarse-grained cave and rockshelter sediments, and from coarse-grained river sediments (Gamble, 1986; Woodward and Goldberg, 2001). Fluvial sediments are the product of flood events and the flood regime can respond in a sensitive way to environmental change – but coarse-grained river sediments are often deposited very quickly and their temporal resolution is limited in comparison to other records. The archaeological records, therefore, are typically limited in resolution and it has become increasingly difficult to make effective comparisons between the cultural and environmental records even for the most recent cold stage. The resolution and quality of many proxy climate records has become far superior to the existing archaeological datasets. Mithen (1999, p. 480) has made this point within a discussion of Mesolithic archaeology and changing Late glacial environments in Britain:

there is in fact an increasing dislocation regarding the fine chronological resolution with which palaeoecologists can reconstruct local environmental history, and the much cruder chronological resolution with which archaeologists have to work.

Figure 13.8 The various environmental archives discussed in this chapter characterised on the basis of their temporal resolution and environmental sensitivity. See the text for further explanation. Plotting the precise location of each archive is somewhat subjective and one could discuss whether cave paintings should be plotted at all, but the purpose of this exercise is to highlight the variability in the nature and quality of data retrieved from different Quaternary archives. Plotting a range of archives using these axes and then justifying their locations can be a very useful exercise for students.

The problem is compounded because rockshelter sedimentary records lack precision and are commonly very ‘noisy’ with complex stratigraphies (e.g., Bailey and Woodward, 1997) and a typical example with a very wide range of sediment particle sizes is shown in figure 13.9. Furthermore, human occupation can disturb the sediment record and alter the fine sediment matrix through physical and chemical processes. This means it can be very difficult to decouple the cultural and environmental signals in rockshelter and cave sediment records (Woodward and Goldberg, 2001). On a positive note, some clastic rockshelter and cave sediment records in the Mediterranean with Middle and Upper Palaeolithic cultural assemblages have been shown to record the influence of some rapid climate change events (e.g., Courty and Vallverdu, 2001; Karkanas, 2001). However, such contexts are unusual and it is difficult to make secure correlations if dating control is limited.

Mithen (1999, p. 481) has argued that archaeologists can only feel frustrated at the relatively poor degree of chronological resolution that appears possible from their data. This mismatch in resolution and dating control means that establishing

Figure 13.9 A section in a rockshelter sediment record showing the wide range of particle sizes (from large boulders to fine clays) and complex stratigraphies that can be encountered. This photograph shows the deep trench at Crvena Stijena in western Montenegro. This is a large limestone rockshelter that contains over 20 m of Quaternary sediments and includes rich Middle Palaeolithic deposits. The photograph contrasts very coarse-grained rockshelter sediments in the central and upper part of the photograph with the lower right section where well-bedded fine-grained alternations of light and dark sediments associated with hearth features are present.

the environmental context of a culture or occupation phase can face many problems, given that climate during the last cold stage is now known to have fluctuated abruptly over timescales of centuries and even decades. Tzedakis et al. (2007) have proposed a novel method for circumventing this problem. They have directly mapped the radiocarbon dates of interest from archaeological contexts onto the high-resolution palaeoclimatic record from the marine sediments of the Cariaco Basin off Venezuela as the latter has been used to develop a radiocarbon calibration curve for the last 50,000 years (Hughen et al., 2004). This approach has provided new perspectives on the environmental context of 'late' surviving Neanderthal groups from Gorham's Cave in Gibraltar.

Quaternary Geography: Sensitivity and Thresholds

Figure 13.10 shows how the tree populations in the three areas of Greece shown in figure 13.6b might have responded to environmental stresses such as the drying and cooling associated with Heinrich Events. The response to such a stress is very different between the three regions and this is a function of local environmental conditions. A key point here is that we should not expect the same response to rapid climate change events in all parts of the landscape as some populations already lie close to their tolerance limit. The schematic representation of temperate tree abundance shown in the lower part of figure 13.10 shows the variable response between each region to climatically induced stress. Tzedakis et al. (2004) use the example of temperate tree abundance, but the variable response could equally be glacier mass balance, karst spring discharge, river sediment yield, or the availability of a key plant or animal resource for a group of Middle Palaeolithic foragers. Some systems may have switched on and off while others showed fluctuations in some measure of abundance or yield. This figure could even represent the population shifts in Neanderthal groups in their refuges in southern Europe before their final demise (see Gamble et al., 2004).

Figure 13.10 A schematic representation of (a) variations of environmental stress encountered by tree populations and (b) the response of the local temperate tree population at the three sites under discussion (modified after Tzedakis et al., 2004). Additional data on each of the three sites are given in table 13.2.

A key point here is that figure 13.10 implies a dynamic and spatially variable Quaternary geography associated with rapid climate change events during the last cold stage and this is in marked contrast to the rather static geography associated with the last cold stage as portrayed in figure 13.4. The response of ecosystems and landscape processes to rapid climate change will be modulated by local and regional environmental conditions and an appreciation of these environmental factors is clearly very important. The ability of human groups to cope with these changes will determine their success in the long term.

More generally, Bowen (1979) has proposed a basic working philosophy for the study of the Quaternary that represents a combination of *geological appraisal* for sequence and *geographical evaluation* for spatial reconstruction, coupled with the particular problems and techniques serving it – be they palaeobotanical, palaeoclimatological or geomorphological (or archaeological in this case). He goes on to argue that the time-space ‘event sequence’ forms the vehicle for ordering the view of the world on this basis. If we consider this approach in relation to figure 13.8, any assessment of the temporal resolution of an environmental archive is essentially a geological appraisal and any attempt to assess the sensitivity of a system will require a geographical evaluation of the lake basin, rockshelter or marine environment in question. At the same time a key aspect of any geographical evaluation must try to factor in the role of environmental thresholds and the potential for a spatially variable response of natural systems to rapid climate change as illustrated in figure 13.10. This problem is analogous to the complex response model put forward by Stan Schumm in the 1970s. He argued that different parts of river basins may respond in radically different ways to an environmental change by either aggrading or incising channel beds for example (Schumm, 1977)

Quaternary Geography and the Human Past

An important challenge is the development of new interdisciplinary approaches that will allow the cultural data from key Middle and Upper Palaeolithic sites to be examined in relation to the high-resolution proxy climate records for the last cold stage. One way of getting around the deficiencies inherent in the records from individual rockshelter and cave sites is to integrate the data from many sites over much larger spatial and temporal scales. Gamble et al. (2004) have compiled a database of over 2,000 radiocarbon dates from across Western Europe and this has allowed them to explore, in very broad terms, population dynamics across Europe from Britain to the Mediterranean between 30,000 and 6,000 BP. In this example, the radiocarbon dates come from archaeological sites across Western Europe and all of them have been calibrated to facilitate comparison with the GRIP ice core record (figure 13.11). This has allowed, for the first time, a regional scale analysis of human response to changing ecological conditions.

The radiocarbon dates have been used as a proxy for Upper Palaeolithic population history. Figure 13.11 shows the importance of southern Europe as a refuge for humans during the last cold stage but it also points to extreme cold tolerance by human populations. The analysis by Gamble et al. (2004) suggests that climate affects population contraction rather than expansion and they also argue that the dispersal of modern humans across Europe took place within wide climatic tolerances. These people had strategies to cope with extreme conditions so that explaining such events by general trends of warming or cooling is not possible.

Figure 13.11 Palaeolithic human geography: using radiocarbon dates as a proxy for population expansion and contraction in three regions of Europe. This figure shows the radiocarbon database of Gamble et al. (2004) plotted by region and shown in relation to the GRIP ice core record for 30 to 6 ka. The population events (1 to 5) discussed by Gamble et al. (2004) are also shown. See text for further explanation. GRIP = Greenland Ice Core Project (modified from Gamble et al., 2004).

Conclusions

With the demonstration that much of the last cold stage was punctuated by a remarkable series of rapid and high-amplitude environmental changes, Quaternary geoscience has entered an exciting and challenging new era. The information on rapid change comes primarily from archives such as the Greenland ice cores, marine sediments in the North Atlantic, and, in Europe, from long pollen and speleothem

records in the Mediterranean basin. A key challenge is to explore the relationship between the Middle and Upper Palaeolithic records in Europe and this new palaeoclimatic framework. However, much of what we know about the human past comes from material preserved in rockshelter and cave sediment records. These records are discontinuous and dating control is often inadequate (Woodward and Goldberg, 2001). New approaches are therefore needed to establish the environmental context of the archaeological record of the last cold stage. Important progress has already been achieved and the next decade will see further advances. If calibration of the radiocarbon timescale back to 50,000 years BP becomes routine practice, it may soon be possible to explore population dynamics across the Middle and Upper Palaeolithic transition in the same way that Gamble et al. (2004) have done for the period between 30,000 and 6,000 years BP. Also, as a more robust dating framework emerges for Upper Palaeolithic cave paintings (using direct AMS dating of the materials used to produce the images), it would be fascinating to explore the relationship between the faunal elements they depict and the records of rapid climate and ecosystem change. The geography of the last cold stage was highly dynamic – both temporally and spatially – with evidence for rapid change in geomorphological processes and ecosystems. The reality of the new records of rapid and high-amplitude climate change means that a geographical perspective on the Quaternary is now more relevant than ever.

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