1. Introduction

The Quaternary is the most recent period of the geologic time scale, spanning roughly the past 2 million years. It is the coolest period of the Cenozoic era and is characterized by dramatic and repeated cycles of global climatic changes, resulting in, among other things, the repeated growth and decay of glaciers worldwide. Of particular interest in archaeology, the Quaternary spans much of human evolution, including the development of the genus *Homo*, the appearance of fully modern human beings, and the evolution of modern cultures and societies. Quaternary environments and environmental changes provided the backdrop for these processes and for most of human prehistory. Moreover, given the impact of Quaternary climate changes on plant and animal communities, on sea level, on rivers, on lakes, and on all other components of the environment, human prehistory must be inextricably linked to Quaternary environmental changes, although the degree and nature of the linkages are hotly debated (e.g., Bell and Walker, 1992; Feibel, 1997; Potts, 1996; Sikes and Wood, 1996; Vrba et al., 1995). Coping with or even (more recently) distancing ourselves from Quaternary environments and environmental changes is arguably a key aspect of human prehistory and evolution. Archaeology is thus one of the Quaternary
sciences and, therefore, understanding the record of the Quaternary and some basic principles of the Quaternary geosciences is an important part of archaeology and geoarchaeology in both research and teaching.

The Earth sciences historically have been employed in archaeology along traditional subdisciplinary lines, such as stratigraphy, geomorphology, geochronology, sedimentology, pedology, and geophysics (e.g., Davidson and Shackley, 1976; Herz and Garrison, 1998; Rapp and Gifford, 1985; Rapp and Hill, 1998; Waters, 1992), but Quaternary geologists have been key players in the development of geoarchaeology (Rapp and Hill, 1998, pp. 1–17). Rapp and Hill further argue that

One can consider geoarchaeology as a component of prehistoric archaeology that, in turn, may be considered a part of geology or paleogeography, which is an aspect of Quaternary geology... These research fields and subdisciplines are part of... a broader framework of natural history and natural science focused on the evaluation of the complete Cenozoic record. (1998, p. 4)

Quaternary geoscience, similar to geoarchaeology, crossects the usual subdivisions of the Earth sciences and indeed goes beyond these subdisciplines to include aspects of the biological sciences, atmospheric sciences, oceanography, and geography. Quaternary geosciences are an important component of the "contextual archaeology" so eloquently and forcefully advocated by Butzer (1982). Studies of the Quaternary period and more typically and explicitly the Pleistocene epoch have long been a component of archaeological research. However, discussions of the significance of Quaternary studies or the basic principles of Quaternary research as a body of knowledge similar to, for example, botany or pedology, are rarely addressed in the archaeological literature, including environmental archaeology and geoarchaeology. A sampling of introductory texts on archaeological method and theory, world prehistory, and North American archaeology published since the mid-1980s (Table 1.1) shows that generally one percent or less of text space is devoted to a discussion of the Pleistocene epoch. The Holocene epoch fares worse, which is startling given the archaeological record of the Holocene, and the Quaternary generally is not mentioned at all (Table 1.1). This tendency is not confined to archaeology texts, however. Most of the few comprehensive volumes on geoarchaeology (Herz and Garrison, 1997; Rapp and Gifford, 1985; Rapp and Hill, 1998; Waters, 1992) have no explicit discussion of Quaternary geoscience, though the topics they do cover would fall under this heading. The notable exceptions are the classic volumes by Butzer (1964, 1971, 1982), which deal directly with concepts of Pleistocene research as a component of geoarchaeology. Some, especially older texts on dating methods in archaeology also included discussions of Pleistocene and Holocene stratigraphy and geochronology (e.g., Oakley, 1964; Wagner, 1998; Zeuner, 1958). Volumes on Quaternary geoscience vary in the amount of attention paid to human evolution and archaeology. Those focusing specifically on Quaternary geology (Bowen, 1978; Dawson, 1992; Ehlers, 1996) pay scant attention to these topics, whereas more comprehensive volumes do (Nilsson, 1983; Williams et al., 1993), though not necessarily in any detail (e.g., Andersen and Borns, 1994; Flint, 1971; ).
This chapter discusses some principles of Quaternary geoscience that have an impact on the study of and understanding of human prehistory. The discussion includes seemingly mundane topics such as the geologic time scale and stratigraphic nomenclature, which are important to understand for precise and accurate communication, similar to an understanding of basic cultural chronologies and associated terminology in archaeology. The chapter also includes a review of current understanding of the Quaternary climate record as revealed in cores from the ocean floors and ice sheets, the mechanisms that forced the climate changes that characterize the Quaternary period, and contemporary approaches to reconstructing Quaternary environments. These issues are important for providing a context for pursuing archaeological questions and for understanding human prehistory.

2. Definitions and Boundaries

The Quaternary period is a subdivision of the geologic time scale. The ordering or grouping of geologic events, rocks, and sediments into a chronological sequence is a key component of "stratigraphy." A discussion of basic stratigraphic principles is beyond the scope of this chapter, but a few key terms and concepts must be introduced. The organization of rocks and sediment based on their age relationships is referred to as "chronostratigraphy." Grouping deposits on the basis of their lithologic characteristics is called "lithostratigraphy."
Figure 1.1. Illustrations of the different approaches that can be taken in the grouping of rocks and sediment into stratigraphic units. (A) The three principal kinds of stratigraphic units, illustrating the diachronous nature of boundaries for lithostratigraphic and biostratigraphic units and in comparison to the synchronous boundaries of chronostratigraphic units (modified from Wagner, 1998, Fig. 1). (B) Stratigraphic subdivisions of a sedimentary sequence showing the different positions of stratigraphic boundaries depending on different stratigraphic criteria.
rocks and sediment according to their fossil content is known as “biostratigraphy.” Lithostratigraphic units and biostratigraphic units can have diachronous boundaries, but chronostratigraphic units always have synchronous boundaries (Fig. 1.1). Moreover, in a sequence of rocks or sediment, the boundaries of different stratigraphic units may not coincide, that is, the rocks or sediment may be grouped in several different ways depending on the stratigraphic approach taken (Fig. 1.1). The principles of stratigraphy are spelled out by Salvador (1994), and excellent discussions of stratigraphy from the perspective of Quaternary studies are provided by Bowen (1978, pp. 84–104) and by Lowe and Walker (1997, pp. 298–323). Further elaboration of specific components of stratigraphy are presented by Wells, in this volume (Chapter 5).

The Quaternary is the younger of the two periods that comprise the Cenozoic era (Fig. 1.2). The Quaternary traditionally is divided into the Pleistocene and the Holocene epochs, terms that seem to be more widely used in archaeology than the term Quaternary. Beyond these basic relationships, however, definitions of the Quaternary, Pleistocene, and Holocene, and the boundaries of these components of the geologic time scale vary significantly and are quite contentious (e.g., Farrand, 1990; Partridge, 1997b; Van Couvering, 1997a). These issues may seem picayune, but are vital to intra- and interdisciplinary communication and understanding. “Stratigraphic nomenclature, like systematic taxonomy, is a tedious means to interesting ends” (Hopkins, 1975, p. 10).

The key here is that ultimately the terms Quaternary, Pleistocene, and Holocene have their origins in and are still part of a formalized (standard) time scale (Harland et al., 1990; NACOSN, 1983; Salvador, 1994). “A geologic time scale (geochronologic scale) is composed of standard stratigraphic divisions based on rock sequences [a chronostratigraphic scale] and calibrated in years [a chronometric scale]” (Harland et al., 1990:1). Thus the subdivisions of the time scale represent intervals of time and the boundaries for each interval are, by definition, synchronous. As discussed below, a physical representation of the boundaries is established somewhere in the world in a real rock section, but elsewhere boundaries have no necessary physical manifestation. The passage of time marking the Pliocene–Pleistocene boundary or the Pleistocene–Holocene boundary in and of itself left no physical evidence (e.g., Goodyear, 1991, 1993), though clearly the change in environmental conditions of the late Pleistocene to those of the early Holocene can be manifested or documented in a variety of physical systems.

For any standard scale to be useful, the intervals must be universally accepted. “...[S]tandardization is intended to give a convenient and stable [time] scale that will not vary with changing opinion” (Harland et al., 1982:41). For example, a yardstick, a tape measure, or a clock would serve no purpose if we had varying views of what constituted an inch, a yard, a meter, or an hour. Units of weights and measures are standardized by international scientific organizations. This is also the case with the geologic time scale, though its definitions are not so crucial to our daily lives, and it has evolved and will continue to do so as we learn more about the geologic past. Moreover, the definitions and terminology of the geologic time scale are based to some extent on pragmatic considerations and acceptance by convention. “The chronostratic scale is a
Figure 1.2. Synthesis of Late Cenozoic time stratigraphy, magnetic polarity, and oxygen isotope ($\delta^{18}O$) stratigraphy. The O-isotope diagram at right shows the details of the late Quaternary record. For both O-isotope curves increasing ice volume is to the left. For the long O-isotope record only warm (interglacial) stages are numbered. In the long isotope record note the change in frequency of glacial-interglacial cycles from a period of ~41,000 years to ~100,000 years at ~0.9 my. Dating of magnetic stratigraphy follows Shackleton et al. (1990). The long record of O-isotope stratigraphy is based on Lowe and Walker (1997). The late Quaternary oxygen-isotope stratigraphy at right is after Martinson et al. (1987).
convention to be agreed rather than discovered, while its calibration in years is a matter for discovery or estimation rather than agreement” (Harland et al., 1990:1). The nomenclature of the time scale “provides a convenient set of labels for slices of time whose artificially selected boundaries are inadequately known” (Hopkins, 1975, p. 10). Ultimately, all stratigraphic subdivisions are to some extent arbitrary and were determined in part by the locations of early geologic field work. The basic terminology of the geologic time scale is now generally accepted and standardized, though for the Quaternary period some terminological issues remain (discussed in the following paragraph). Otherwise, the points of contention generally focus on deciding on and dating the boundaries.

At its most basic level, the Quaternary period is a time of relatively cool global climate at the culmination of long-term cooling that characterizes the Cenozoic era. Within this period of relative cooling were dramatic and repeated cycles of climate change, typified by the growth and decay of glaciers. Hence, the Quaternary is often called the “Ice Age.” The cycles of glacial expansion and contraction are referred to as “glacial” and “interglacial” stages with superimposed “stadials” and “interstadials” (Lowe and Walker, 1997:8). A glacial stage was a prolonged period of cooling when major expansion of ice sheets and glaciers took place. A stadial, in contrast, was a shorter cold episode when local ice advance occurred. An interglacial stage was a warm interval when temperatures reached or exceeded those of the present time and when ice coverage of the Earth’s surface was minimal. An interstadial was a relatively short-lived period of warming within a glacial stage, but temperatures did not reach the levels of today (see also the discussion of Bond cycles that follows).

The Pleistocene epoch comprises all of the glacial–interglacial cycles of the Quaternary except for the current interglacial called the Holocene epoch. Thus, the Pleistocene also has been referred to as the “Ice Age.” The Holocene, significantly, is not unique geologically or environmentally relative to any other interglacial stage and, therefore, is an arbitrary subdivision of the Quaternary period. As Sherratt (1997) correctly observes, “Over 90% of [the Quaternary] period has been cooler and dryer than the Holocene, so contemporary conditions are unrepresentative. Archaeologically, though, the Holocene is the time during which food production and complex societies appeared. Archaeologically and anthropologically, therefore, the Holocene is significant.

On a conceptual level, differentiating the Holocene epoch from the Pleistocene epoch has generated considerable discussion (Farrand, 1990; discussed in the following text), but these terms are perhaps more problematic at the level of everyday usage. An unfortunate tendency in archaeology as well as in Quaternary studies is to look on “The Pleistocene” as something distinctly different from “The Holocene” (Fagan, 1997:112-115; Renfrew and Bahn, 1996:120; Wenke, 1984:52). It is not. The Holocene is simply the latest in a long series of interglacial stages (discussed further below). Some investigators also refer to the “Pleistocene–Holocene transition” and infer the passage of some time (several thousand years) (e.g., Walthall, 1998). Certainly the environmental conditions at the end of the Pleistocene (e.g., at the end of the last glacial period) evolved over several thousand years into Holocene (e.g., postglacial environments), but the
Pleistocene–Holocene “transition” is a boundary on the geologic time scale and as such represents a moment in geologic time.

So how are Quaternary, Pleistocene, and Holocene defined? As noted, the most common informal definition of the Pleistocene and Quaternary is “The Ice Age.” Another view was that this was “The Age of Man” or “Age of Humanity,” referring to the idea that the first appearance of humans coincided with the beginning of the Pleistocene (Farrand, 1990). Vertebrate and invertebrate faunal changes were formally proposed as defining criteria, following long-standing geologic tradition. There are substantial problems with most of these definitions, however. The first hominids preceded the onset of the Pleistocene epoch by 1 to 2 million years (regardless of one’s view on dating the beginning of the Pleistocene, discussed in the following text). Vertebrate faunas were evolving throughout this time, and there is no globally significant, clearcut change in faunal assemblages. Scattered, small, high-latitude and high-altitude glaciers appeared in the late Cenozoic long before more substantial lower latitude and lower altitude glaciers. Likewise, environmental cooling was a continuous process through the late Cenozoic. As summarized by Farrand (1990:19) “From the time of Desnoyers and Lyell [both 19th-century geologists who helped ‘construct’ the geologic time scale] to the present, it has been noted that the passage from the Tertiary to the Quaternary, or from the Pliocene to the Pleistocene, was generally one of transition, not of abrupt change.”

Attempts at standardizing the geologic time scale began in the 19th century, but not until after the Second World War did standardization become a reality (Harland et al., 1990, pp. 2–3). This work was and continues to be under the auspices of the International Geological Congress (IGC) and the International Union of Geological Sciences (IUGS), though ultimately the adoption of terms, definitions, and dates is by agreed convention among workers in the field. Subdivisions of the time scale are standardized at their boundaries only. The conceptual basis for each boundary is a marine biostratigraphic sequence. This definition goes back to the roots of the geologic time scale. Lyell (1833, 1839), for example, subdivided the Tertiary period on the basis of percentage of living Mollusca represented in fossil assemblages. For the Pleistocene (initially viewed as part of the Tertiary) Lyell (1839) proposed that this term be applied to deposits having more than 70% modern molluscs (see discussion in Farrand, 1990:17). Significantly, this most enduring of definitions was proposed before and independently of the recognition that the Pleistocene epoch was a time of glaciation. Under the new procedures, a boundary is agreed upon based on the approximate position in a biostratigraphic sequence that best fits existing usage of the particular subdivisions of the time scale (Harland et al., 1990:3).

Once the general biostratigraphic concept of the boundary is agreed on, a stratigraphic section somewhere in the world is selected to be the physical representation of the boundary, called a “boundary stratotype.” The boundary is a unique rock section in which a time horizon is defined as a universal standard of reference for dating purposes. Exposed marine sections are usually used because marine invertebrate fauna or faunal assemblages can change rapidly, they can be correlated over wide regions, and because marine sections tend to be
more continuous (i.e., have fewer time gaps) than terrestrial sections. Beyond its representativeness, the boundary stratotype also is selected on the basis of its completeness and access (Harland et al., 1990:3).

2.1. The Pliocene–Pleistocene Boundary

The Pliocene–Pleistocene boundary was one of the first boundaries with which the IGC attempted to deal (in 1948). It has proven to be a tough boundary to establish and date (see the detailed discussion in Nikiforova and Alekseev, 1997, and also Harland et al., 1990:68, from which the following is distilled; and Mauz, 1998). Several decades passed following the initial 1948 discussions before a boundary and stratotype were proposed. The first section considered (in 1972) was Le Castella, Italy (first proposed by Grignouix, 1913), but problems with the section soon appeared and in 1977 a section at Vrica, Italy was agreed on. The Vrica section, fully discussed and described in Van Couvering (1997b), still stands as the boundary stratotype for the Pliocene–Pleistocene boundary. Most investigators agreed to define the Pliocene–Pleistocene boundary within the section on the basis of the appearance of certain cold-water marine fauna in the Mediterranean. The idea is that such fauna would provide clear evidence of significant global cooling, including low-latitude and otherwise warm-water settings.

Historically, chronometric estimates for the age of the base of the Pleistocene range from 0.6 to 4 Ma (Haq et al., 1977). Establishment of a boundary stratotype has focused the issue but hasn’t necessarily settled it. Within the Vrica section, the boundary was placed at the top of the Olduvai normal polarity zone (Fig. 1.2), dated to 1.64 Ma (Aguirre and Pasini, 1985; Tauxe et al., 1983). The age of 1.6 Ma was widely adopted; it was incorporated, for example, into the standard time scale of the Geological Society of America (Palmer, 1983) and the U.S. Geological Survey (Hansen, 1991, Fig. 15). Reinvestigation of the section and some revision of the geomagnetic polarity time scale resulted in a revised age of 1.796 (1.8) Ma for the boundary (Fig. 1.2; Pasini and Colalongo, 1997).

Selection of the Vrica section as a Pleistocene boundary stratotype and placement of the boundary has never had universal acceptance (Partridge, 1997b). The issues are several (well summarized by Mauz, 1998; see also the debate between Morrison and Kukla, 1998, and Aubry et al., 1998). Some believe that the definition of the base of the Pleistocene should be expressly climatic and should take into account evidence of significant global cooling between 3.0 and 2.0 Ma (Partridge, 1997a), whereas others question the interpretation of the section (e.g., Jenkins, 1987). Several investigators now argue that the boundary should be placed at the Gauss–Matuyama paleomagnetic reversal (Fig. 1.2), that is, moved back to 2.6 Ma (formerly dated at 2.4 Ma e.g., Ding et al., 1997; Ehlers, 1996:3; Morrison and Kukla, 1998; Partridge, 1997a; Suc et al., 1997). The arguments are based on evidence for significant cooling around the G–M boundary in both marine and terrestrial (loess) records along with the ease of correlation of the G–M boundary.

The issue is far from resolved, but most earth scientists, at least in the United States, seem to follow the recommendation to use 1.8 Ma (formerly 1.6 Ma; e.g.,
Berggren et al., 1995a,b; Harland et al., 1990; Woodburne and Swisher, 1995). In any event, investigators working with late Pliocene and early Pleistocene localities should explicitly state their definitions of the boundary.

2.2. The Pleistocene–Holocene Boundary

The Pleistocene–Holocene boundary is one of the most difficult boundaries to deal with because: (1) we know so much about the last glacial–postglacial transition; (2) the nature of the transition varied significantly from region to region, and among different components of the environment (e.g., climate, flora, fauna); and (3) dating resolution is much finer than the length of the transition. Over the years, arguments for the age of the boundary ranged from 20,000 to 4,000 yrs BP (Hopkins, 1975; Morrison, 1969). Indeed, some argue that the Pleistocene–Holocene boundary should be formally recognized as diachronous depending on local records (Watson and Wright, 1980), and others propose that the term should be abandoned altogether because the Holocene simply represents the current interglacial (Flint, 1971:384). These arguments have merit, but neither is likely to be accepted. The general concept of the Holocene epoch and the usage of the term are too well established and we have such a vast amount of data for it compared to any other subdivision of the Quaternary period. The concept of the Holocene epoch has proven especially useful in archaeology because the Pleistocene–Holocene transition was a time of significant changes in the archaeological record, followed soon after by the development of complex societies (e.g., Eriksen and Straus, 1998; Straus et al., 1996). A diachronous boundary or at least the provision for differing boundary criteria from region to region (e.g., Haynes, 1991; Watson and Wright, 1980) is contrary to the concept of chronostratigraphy and a standard time scale. This would be akin to allowing different places to have their own definition of a day because day length varies latitudinally and seasonally.

In 1969 the International Congress for Quaternary Research (INQUA) proposed that the Pleistocene–Holocene boundary be placed at 10,000 yrs BP and that a suitable boundary stratotype be searched for in a fossiliferous marine section in Sweden (Hagman, 1972; Harland et al., 1990:71, sec. 3.21.5). The proposed date represents a good midpoint between full glacial conditions of the terminal Pleistocene and maximum warming of the early Holocene, and, as Hopkins (1975) observed, “we place the onset of the Holocene Epoch at 10,000 B.P. simply because that’s a nice round number” (p. 10). The age of 10,000 yr BP for the boundary seems to be gaining general acceptance based on its wide adoption and usage (e.g., Hansen, 1991; Harland et al., 1990, Fig. 15; Palmer, 1983; Roberts, 1989; Woodburne and Swisher, 1995). Perhaps the most noteworthy aspect of the INQUA proposal is that this is the only instance of a boundary stratotype being proposed on the basis of an absolute age and for a suitable section to be found that best documents the date marking the full-glacial–postglacial transition.
2.3. Stratigraphic Subdivisions

The most common subdivision of the Pleistocene time scale is a tripartite ("early," "middle," and "late") scheme (Fig. 1.2). The early–middle Pleistocene boundary is placed at the Brunhes–Matuyama polarity reversal, 788 ka (Fig. 1.2) (Harland et al., 1990:68, sec. 3.21.2). The middle–late Pleistocene boundary is placed at the beginning of marine oxygen isotope stage 5e (Fig. 1.2; see the following section) Harland et al., 1990:68–69, sec. 3.21.2), which represents the beginning of the last interglacial period before the Holocene, dated to ca. 125 ka (following Winograd et al. 1997, though interpretations vary on the dating of this boundary). A formal nomenclature for a tripartite subdivision of the Quaternary has not been proposed but seems appropriate given, for example, the wide use of the term "Late Quaternary" (e.g., Bell and Walker, 1992; Bryant and Holloway, 1985; Dawson, 1992; Wright, 1983). The same standards that apply to the Pleistocene probably can apply to the Quaternary.

An important distinction here is the difference between "early," "middle," and "late" and "lower," "middle," and "upper." The former are geologic time terms, used to refer to subdivisions of real time (e.g., the genus Homo appeared in early Pleistocene time). In contrast, the latter trio of terms refer to subdivisions of the chronostratigraphic record itself, that is, a real rock sequence (lithostratigraphy) on which time subdivisions are based (e.g., the bones of Homo are found in lower Pleistocene rocks).

3. Glacial–Interglacial Cycles

Since the beginning of the 20th century, geologists have recognized that the Pleistocene epoch was characterized by a series of dramatic environmental changes, most famously represented by the advance and retreat of glaciers. For much of the 20th century, the evidence for these environmental cycles was used to subdivide the Pleistocene. The best known subdivisions were the glacial–interglacial stages of the Alps (Günz-Mindel-Riss-Würm, oldest to youngest) and the Midwestern United States (Nebraskan-Kansan-Illinoian-Wisconsin, oldest to youngest). These two glacial stratigraphic sequences in particular, along with several others from Europe, came to dominate much of the thinking about the Quaternary record worldwide such that most Pleistocene deposits, soils, and landforms were usually somehow "fit" into or otherwise correlated with these schemes. This situation is well described by Bowen (1978:10–56) and by Ehlers (1996:323–325, 355–357), and is illustrated in Wright and Frey (1965) and in Flint (1971).

With the expansion of academic and governmental research into the Quaternary following the Second World War, and with the development of numerical dating methods, many investigators began to realize that the simple fourfold stratigraphic sequences for the Midwest and for Europe were grossly oversimplified. For example, studies of glacial stratigraphy and intercalated volcanic ashes
on the Great Plains and the Midwestern United States clearly showed that there were more than four glacial–interglacial cycles represented and that the classic terminology for all pre-Illinoian deposits should be abandoned (Boellstorff, 1978; Hallberg, 1980a,b). In eastern Europe, a classic investigation of loess stratigraphy showed that there were perhaps 17 glacial–interglacial cycles in the past 1.7 million years (Fink and Kukla, 1977; Kukla, 1975, 1977).

The most far-reaching advances in understanding and classifying the climate cycles of the Quaternary, however, came from studies of sediments on the floors of the ocean and from ice locked in glaciers. The basic assumption and condition that allowed the deep ocean research is that parts of the ocean basins have been the sites of essentially continuous sedimentation during much or all of the Quaternary (and earlier) in contrast to terrestrial settings with stratigraphically incomplete and regionally discontinuous records. On glaciers, very high elevations have extremely low rates of ablation so that snow accumulation has been essentially continuous. Among other contributions, the deep sea work demonstrated (and continues to show) the lengthy, cyclic, and complex nature of Quaternary environmental changes, and it also provided an exceptional standard scale for comparison and correlation of all other Quaternary stratigraphic records. The glacial ice, though not spanning as much time as the ocean sediments, provides a high resolution record of precipitation amounts, air temperature, atmospheric composition, and explosive volcanic activity, among other kinds of proxy indicators.

Beginning in the 1950s, cores recovered from the ocean basins have been analyzed for their isotopic, paleontological, and magnetic characteristics. These studies revolutionized thinking about Quaternary climates. For the purposes of this discussion the most pertinent issue is the variation in composition of oxygen isotopes in marine fossils. At scales of tens to hundreds of thousands of years, the ratio of $^{18}O$ to $^{16}O$ varies significantly (Fig. 1.2). Initially, this variation (expressed as $\delta^{18}O$) was believed indicative of fluctuations in global temperatures (Emiliani, 1955; Epstein et al., 1953; Urey, 1947), but subsequent studies indicated that most of the changes were due to changes in the global extent of glaciers (e.g., Shackleton, 1967). Regardless, the $\delta^{18}O$ curves illustrate worldwide environmental changes throughout the Quaternary. The usual approach taken for interpreting the cores is as an indicator of ice volume (these issues are well outlined and explained by Bowen, 1978:61–69, and by Bradley, 1985:178–189). Because it is the lighter of the two isotopes, $^{18}O$ is preferentially removed from the oceans by evaporation. Water or ice subsequently precipitated will be enriched in $^{16}O$. As glaciers build up, therefore, they become enriched in $^{18}O$, while ocean water becomes depleted in $^{18}O$ relative to $^{16}O$. When glaciers melt at the onset of an interglacial or interstadial cycle, the $^{16}O$-enriched waters return to the oceans, altering the $^{18}O/^{16}O$ ratio.

Studies of hundreds of cores from across all the world's ocean basins show that these curves can be correlated and are synchronous globally, thus providing a worldwide standard for comparison of Quaternary environmental changes (Bradley, 1985:178–189). "It is highly unlikely that any superior stratigraphic subdivision of the Pleistocene will ever emerge" (Shackleton and Opdyke,
1973:48). Indeed, this seems to be the case and the curves are widely used as a standard in correlation of both marine and terrestrial stratigraphic records. The fluctuations in the oxygen isotope curves were assigned numbered “Stages” beginning at the top (most recent, Fig. 1.2). Periods of increased ice volume (glacial periods) have even numbers and periods of decreased ice volume (interglacial periods) have odd numbers (with the exception of Stage 3, which is an interstadial period). Boundaries between stages are at the midpoints between maximum and minimum values (Fig. 1.2). The Holocene epoch, the present interglacial, correlates to oxygen–isotope Stage 1, for example. The last full glacial period (e.g., the late Wisconsinan in the midwest United States, the late Wurmian in the Alps), is Stage 2, the penultimate glaciation (the Illinoian in the Midwest) is Stage 6, and so on.

A glance at the oxygen–isotope curve clearly shows that there were many more than four glacial–interglacial cycles (Fig. 1.2). The cycles have a period of about 100,000 years for the past 1 million years, and have a period of 41,000 years prior to that back to about 2.5 million years (Ruddiman et al., 1986; Shackleton et al., 1990), yielding strong evidence for approximately 30 glacial–interglacial cycles during the Quaternary period.

In recent decades, and especially in the 1990s, cores from glaciers (mostly but not exclusively from Greenland and from Antarctica) have begun to provide an unprecedented record of a variety of characteristics of the atmosphere spanning much (and in some cases most) of the late Quaternary (see Bradley, 1999:125–190, for an excellent summary of ice core studies). The ice core studies brought about yet another revolution in our understanding of Quaternary paleoclimatology “by providing high resolution records of many different parameters, recorded simultaneously at each location” (Bradley, 1999:153). Ice cores are not as numerous as ocean cores and ice cores do not provide the time depth of deep-sea cores. Less than two dozen ice cores go back to the last glaciation; a few extend back to the penultimate glaciation (oxygen isotopes Stage 6 Bradly, 1999:126, Table 5.2). However, the layers of ice in the ice cores tend not to be subjected to the mixing that characterizes the deep ocean cores, and thus some provide an annual record of Holocene and even late Pleistocene atmospheric variation (e.g., Thompson et al., 1985). In addition, a wider variety of dating techniques can be applied to ice cores.

The cores from glaciers have yielded a number of significant results. For example, levels of atmospheric dust (which can affect the global energy balance) were much higher during glacial periods, and the composition of gases in the atmosphere (which can influence radiation) changed over glacial–interglacial cycles (e.g., Mayewski et al., 1993). The cores also provide a record of explosive volcanic eruptions that can influence climate. Perhaps the most significant result to come out of the ice core research, however (certainly from an archaeological viewpoint), is evidence that Holocene climates were relatively stable whereas climates during cold (glacial) stages fluctuated rapidly between two or more modes (e.g., Adams et al., 1999; Taylor et al., 1993). For example, Dansgaard et al. (1993) identified 24 interstadial episodes between 12,000 and 110,000 yrs BP. This issue is discussed further in the following section.
4. Causes of Quaternary Climate Cycles

The question of what caused Quaternary climate changes has been with us for as long as the concepts of the Quaternary and Pleistocene have. Until the 1970s, no satisfactory, generally acceptable theories were available, and the issue remained a fundamental problem in Quaternary research (Flint, 1971). Flint (1971:788–809) summarizes the theories prevalent at the beginning of the 1970s. Most broadly they fall into six categories: (1) variation in solar emissivity, (2) veils of cosmic dust, (3) geometric variations in the Earth’s orbital parameters, (4) variations in the optical depth (transmissivity and absorptivity) of the Earth’s atmosphere (due, for example, to volcanic eruptions), (5) lateral and vertical movements in the Earth’s crust, and (6) changes in the system of ocean/atmosphere circulation. At the time the biggest obstacle to sorting out and evaluating these ideas was lack of data. That situation began to change dramatically shortly after Flint’s (1971) volume was published, and more and more data have become available at an ever-increasing rate.

Several of the processes listed previously appear to play roles in changing the earth’s climate, but at different time scales. Cooling of the earth’s surface to the point where glaciers can exist and grow probably is linked to tectonic movement of continental plates to high (northern) latitudes (late Mesozoic to today), the opening of the North and South Atlantic and the connection of the North Atlantic to the Arctic Ocean, the opening of the Bering Strait (late Mesozoic to today), the closing of the Isthmus of Panama (connecting North and South America and significantly affecting ocean circulation in the late Tertiary), and tectonic uplift of mountain ranges, especially the Tibetan Plateau (late Tertiary; summarized by Bell and Walker, 1992:65–66; Ehlers, 1996:7–8; Maslin et al, 1998; Partridge et al., 1995; Williams et al, 1993:15–25). These processes do not account for the cyclicity of climate change within the Quaternary, however.

The key to the “pacemaker of the Ice Ages” came with the discoveries of the long and complex record of climate changes and ice volume combined with an old idea that climate cycles were due to variations in the geometry of the Earth’s orbit around the Sun (a fascinating detective story well told by Imbrie and Imbrie, 1979). The basic idea of the “astronomic theory” was proposed in 1842 by James Croll, but the person who provided the most detailed and elaborate calculations and whose name is most closely associated with it is Milutin Milankovitch, who worked on the idea from 1910 to 1940 (Imbrie and Imbrie, 1979). His ideas generated considerable interest, but few data were available to support them. By the mid-1970s, however, a variety of new dating methods were applied to the deep-sea cores and the global significance of the deep-sea record became clear, whereas the loess studies in central Europe showed that the terrestrial glacial record was comparable to and correlated with the ocean record. The results of this research created a revolution in thinking about Quaternary history (Imbrie and Imbrie, 1979). The impact on the Quaternary sciences was comparable to the impact of plate tectonic theory in geology or of Darwinian evolution in biology.
Changes in the earth's orbit around the Sun affect the seasonal and hemispheric distribution of the insolation, which is the radiation influx or the amount of solar radiation reaching the earth's surface (Fig. 1.3). These changes appear to influence climate though the linkages remain unclear. Three orbital factors are involved (well described and discussed by Bell and Walker, 1992; Dawson, 1992; Ehlers, 1996; Imbrie and Imbrie, 1979; and Lowe and Walker, 1997; among others); (Fig. 1.3). Eccentricity refers to elongation in the elliptical path of the Earth's orbit around the Sun. Variations in the shape of the path change in 100,000-year cycles. Obliquity refers to the tilt of the Earth's axis of rotation relative to its orbital plane. Today the tilt is 23.5° but it varies between 24.5° and 22.0° in 41,000-year periods. Increasing tilt increases the amount of solar radiation reaching the poles in the summer and increases seasonal contrasts. Precession refers to the "wobble" of the Earth's axis as it spins. This wobble describes a circle with a period of 19,000 to 23,000 years. As noted previously, the 100,000-year cycles seem to have dominated glacial–interglacial cycles in the later half of the Quaternary, and 41,000-year cycles dominated the first half (Fig. 1.3). Variations in insolation due to changes in eccentricity appear weak so why the 100,000-year period is so strong remains a question as does the reason why the cyclicity changed from 41,000 years to 100,000 years (see Raymo, 1998, and Bradley, 1999:35–46 for further discussion).

Other factors such as volcanic emissions, ice sheet instability, and characteristics of ocean circulation likely play a role in changing the climate, particularly at millennial time scales. Volcanic eruptions and the injection of aerosols into the atmosphere are known to have dramatic short-term effects on climate, and some investigators have suggested that fluctuations in climate at scales shorter than Milankovitch cycles may be the result of increases in volcanic eruptions (Hammer et al., 1981; Lamb, 1982; Porter, 1986). Others have suggested that volcanic eruptions can modulate the effects of Milankovitch forcing (Bryson, 1989; Rampino and Self, 1993) and that rapid climatic changes can force volcanism (McGuire et al., 1997; Zielinski et al., 1996).

Evidence for cyclic instability of ice sheets at time scales shorter than the Milankovitch periodicities recently has been recognized in cores from the Greenland ice sheet and from North Atlantic sediments (summarized by Bradley, 1999; Broecker, 1995, Lowe and Walker, 1997, and ). The climate of the last glaciation was composed of a series of cooling cycles of 10,000 to 15,000-year duration (Bond cycles; Fig. 1.4) (Adams et al., 1999; Bond et al., 1993). The Bond cycles were composed of a series of cold stadials, culminating in the coldest stadial of approximately 1000 years duration (Fig. 1.4), associated with the massive release of icebergs into the North Atlantic (Heinrich events; Adams et al., 1999; Andrews, 1998; Bond and Lotti, 1995; Broecker et al., 1992; Heinrich, 1988). The Bond cycles included periods of relatively warmer climatic conditions (Dansgaard–Oeschger events) lasting 2000 to 3000 years (Fig. 1.4; Adams et al., 1999; Dansgaard et al., 1993; Johnsen et al., 1992). Following the Heinrich event that culminated a Bond cycle was an abrupt shift to a warmer climate (an interstadial; Bond and Lotti, 1995; Bond et al. 1993) and then gradual cooling that marked the beginning of the next Bond cycle (Adams et al., 1999). The causes of these various cycles are unclear; they may have been due to internal
Figure 1.3. Key components of the variations in Earth's orbit around the Sun (Milankovich cycles) and their effect on Quaternary climate. (A) Schematic representation of Earth's orbital elements (modified from Ruddiman and Wright, 1987, Fig. 4). (B) Earth–Sun geometry for ca. 18,000, ca. 15,000–12,000, ca. 9000, and ca. 6000–3000 yrs BP, and the present. Perihelion (minimum distance from the sun) is in January at present and in July ca. 9000 yrs BP, and tilt is greater at ca. 9000 yrs BP than at ca. 18,000 yrs BP and at present (modified from Kutzbach and Webb, 1993, Fig. 2.1). (C) Variations in eccentricity, obliquity, and the precessional index over the past 800,000 years. ETP is a composite curve constructed by normalizing and adding the three time series. The scale for obliquity is in degrees and for ETP in standard deviation units. (D) The δ18O curve showing the similarity between it and the ETP curve in (C, C and D modified from Lowe and Walker, 1997, Fig. 1.8).
Figure 1.4. Generalized diagram of temperature fluctuations (warm is up) during the last full glacial in the North Atlantic illustrating the relationship of Bond cycles (B), Dansgaard-Oeschger events (D-O), Heinrich events (H1–H6), and the Younger Dryas (YD, modified from Lowe and Walker, 1997, Fig. 7.13).

Oscillations of the ice sheets to external climatic forcing, or more likely, to a complex combination of factors (Adams et al., 1999; Andrews, 1998; Berger, 1990; Bradley, 1999:261–268). The Heinrich events, however, probably resulted from ice sheet instability and collapse. The effects of these cycles beyond the Greenland ice sheet and the North Atlantic are unclear, but at least some of the cycles may be globally significant (e.g., Adams et al., 1999; Allen and Anderson, 1993; Bradley, 1999; Lowe et al., 1994; Lowell et al., 1995;).

Regardless of the causes of these different cycles, the apparently rapid changes in environmental conditions have significant archaeological implications because the rate of change may have approached the scale of human life spans (Adams et al., 1999; Dansgaard et al., 1993; Johnsen et al., 1992). This would mean that prehistoric populations would have to adapt to rapid and dramatic climate shifts. The best known of the rapid cooling cycles is the “Younger Dryas” dated to 11,000 to 10,000 BP, similar to and sometimes characterized as a Heinrich event (Broecker, 1992, 1995; Keigwin and Jones, 1995). A variety of paleoenvironmental and even archaeological events dated to this period from around the world have been correlated to the Younger Dryas (Anderson, 1997; Haynes, 1991; Sherratt, 1997).

Changes in thermohaline circulation of the oceans, the movement of ocean water masses due to temperature and salinity (density) gradients, has been recognized in the 1990s as being linked to late glacial climate changes (e.g., Bond et al., 1993; Boyle, 1995; Broecker, 1991). Proposed causes of the changes include both discharge of massive amounts of glacial meltwater into the oceans (Broecker et al., 1989, 1990) and the periodic release of iceberg “armadas” associated with Heinrich events (Baumann et al., 1995; Broecker, 1994). The linkages between climate, ocean circulation, and ice sheets, however, are probably much more complex than these proposals suggest (e.g., Adams et al., 1999; Anderson, 1997; Bradley, 1999:260–275; Lowe and Walker, 1997:362–365).
These processes do not, however, account for abrupt climate changes and possible changes in ocean circulation during interglacial periods (Stager and Mayewski, 1997).

5. Reconstructing Quaternary Environments: Data versus Models

Traditionally the most direct bearing of Quaternary studies on archaeology probably is the application of methods for reconstructing paleoenvironments. The methods for such reconstructions fall into two broad categories: proxy records and computer simulation models. These approaches provide distinctly different kinds of information, distinctions that are not always fully appreciated by field investigators. Each category also has its advantages and disadvantages.

Proxy records are organic and inorganic remains that provide an indirect indicator of past environments (Bell and Walker, 1992:11). This approach relies on the principal of uniformitarianism, which states that our understanding of geological and biological processes operating today can be used to reconstruct the past (Rymer, 1978). Proxy indicators are derived from glaciological (ice core), geological, biological, and historical records (Table 1.2; Bell and Walker, 1992; Bradley 1985, 1999; Lowe and Walker, 1997). Plant and animal remains are used to reconstruct floral and faunal communities that in turn provide clues to environmental and even climatic conditions. Inorganic remains such as sediments, soils, and stable isotopes can provide information on conditions of formation (e.g., depositional environments and weathering conditions). These methods have been used in archaeology and in other Quaternary sciences for environmental reconstructions for decades. For example, the study of vertebrate remains has been a component of archaeological research since the middle of the 19th century (Grayson, 1983), and palynology was incorporated into archaeology since the inception of pollen studies earlier in the 20th century (Bryant and Holloway, 1983). Indeed, archaeological research has been an important driving force in the development of some paleoenvironmental methods such as phytolith analysis (Piperno, 1988: p. 1–10).

Computer simulation climate models are, at their most basic level, mathematical computations of climate conditions given a set of specified and calculated parameters (see Bradley, 1999, pp. 471–505, for an excellent summary of paleoclimate models). The best known models are General Circulation Models (GCMs), which attempt to simulate the three-dimensional structure and flow of the atmosphere (Kutzbach, 1985; Street-Perrott, 1991). Their development resulted from the availability of fast and powerful computers. In the models, Earth’s surface is represented by a grid, usually 4 to 10°. For each grid cell, a number of values can be prescribed or calculated at various levels from the surface up into the atmosphere (usually 10–20 levels, with more near the surface).

One of the better known applications of a GCM for reconstructing Quaternary climates is COHMAP (the Cooperative Holocene Mapping Project; COHMAP, 1988; Webb, 1998; Wright et al., 1993). This project modeled global
Table 1.2. Sources of Proxy Data for Paleoclimate Reconstructions

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<tr>
<th>Glaciological (Ice Cores)</th>
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<tr>
<td>Oxygen and hydrogen isotopes, major ions</td>
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<td>Gas content in air bubbles</td>
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<td>Trace elements and microparticle concentrations (e.g., dust)</td>
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<td>Physical characteristics</td>
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<td>Geological</td>
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<td>Marine (ocean sediment cores)</td>
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<td>Microfossils</td>
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<td>Oxygen isotopes (of Foraminifera)</td>
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<td>Sediment mineralogy and geochemistry</td>
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<td>Eolian dust and pollen</td>
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<td>Ice-rafted debris</td>
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<td>Clay mineralogy</td>
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<td>Terrestrial</td>
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<tr>
<td>Glacial landforms and deposits</td>
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<td>Periglacial and other mass-wasting landforms and deposits</td>
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<td>Eolian landforms and deposits</td>
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<td>Fluvial landforms and deposits</td>
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<td>Lacustrine landforms and deposits</td>
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<td>Cave deposits</td>
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<td>Mire and bog deposits</td>
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<td>Soils and other weathering characteristics</td>
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<td>Tree rings</td>
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<td>Pollen</td>
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<td>Phytoliths</td>
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<td>Plant macrofossils</td>
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<td>Weather records</td>
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<td>Weather-dependent phenomena</td>
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<td>Phenological records</td>
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*Modified from Bradley (1985, 1999), following Lowe and Walker (1997).*

late-Quaternary climates at 3000-year intervals from 18,000 yrs BP (full glacial time) to the present. Their GCM, described by Kutzbach (1987), by Kutzbach and Webb (1993), and by Kutzbach and Ruddiman (1999) incorporated principles of atmosphere dynamics based on equations of fluid motion, radiative and convective processes, and condensation and evaporation; and prescribed levels of incoming solar radiation (based on orbital parameters), atmospheric CO₂ concentration, sea-surface temperature, sea-ice limits, snow cover, land albedo, effective soil moisture, sea level, ice sheet height, volume, and extent, and continental topography. The model has nine vertical levels at a grid scale of $4.4^\circ \times 7.5^\circ$ and was calculated for January 16 and July 16 for each of the 3000-year "snapshots." A newer version of the model (Kutzbach et al, 1998) includes interactive
components for soil moisture, snow hydrology, sea-ice, and mixed-layer ocean temperature, and is configured to simulate the full seasonal cycle.

The results of the COHMAP modeling include maps of each time slice illustrating large-scale patterns of circulation and surface climate, jet stream locations, and regional averages of temperature, precipitation, and precipitation minus evaporation. The latest version of the model (Kutzbach et al., 1998) also simulates major biomes. The models are tested by producing a model of modern conditions for comparison with known conditions and by comparing model results for each time slice with proxy evidence from that time. The numerical simulations of GCMs have been able to reproduce aspects of paleoclimate indicated by proxy records (Street-Perrott, 1991; Wright et al., 1993) and, moreover have provided insights into the significance of factors such as Milankovitch forcing, ice sheet coverage, the effects of seasonality and vegetation feedbacks, and explanations of regional linkages of climate such as the evolution of monsoon climates and the effects of tectonic uplift (e.g., Kutzbach et al., 1993; Ruddiman and Kutzbach, 1989; TEMPO, 1996; Webb et al., 1993).

Another approach to climate modeling of particular relevance in archaeology is the "archaeoclimatic model" developed by Bryson and Bryson (1997a,b). It is the inverse of and a complement to the GCM. The model presents computations of climate for a specific locality (such as an archaeological site) over time, whereas the GCMs yield climate simulations for a point in time around the globe. Archaeoclimatic modeling is specifically for archaeologists working on sites with lengthy records. The model includes the heat budget of Earth, incoming solar radiation flux through time as determined by Milankovitch forcing and modulated by volcanic eruptions, and a model of surface ice cover. The locations of major climate systems such as the jet stream and the intertropical convergence zone are calculated for each hemisphere at 200 year intervals back to 14,000 BP and then at 500-year intervals back to 40,000 yrs BP. Synoptic climatology provides the link between the past locations of major circulation features and the climate of a particular site. The results provide estimates of mean temperature and precipitation by month at the 200- and 500-year intervals.

6. Discussion and Conclusions

Archaeology is a Quaternary science, arguably one of the most fundamental ones. The Quaternary period is unique in Earth history in having anatomically modern humans or their predecessors present throughout the period. This characteristic of the period has driven much of the interest and research into the Quaternary as scientists seek to understand human biological and cultural evolution, the relationship of this evolution to environmental changes, and the potential effects of and adaptations to future environmental changes. The Quaternary sciences, therefore, should be an intrinsic component of archaeological teaching and training. Quaternary science encompasses a wide array of disciplines and subdisciplines, similar to archaeology, and archaeologists cannot be expected to be familiar with, much less master, all of these areas. There are several key aspects
of Quaternary studies that are fundamental, however, and should be familiar to all of those studying the history of the Earth and its occupants over the past 2 million or so years.

The basic terminology of the geologic time scale is a fundamental issue of communication, although terminological problems can easily become exercises in semantics, if not nit-picking. Understanding the history, basic concepts, and current conventions regarding the time scale in general, and the Quaternary, Pleistocene, and Holocene in particular, are as important as understanding the meaning of, for example, Paleoindian and Archaic or the Upper Paleolithic and Mesolithic. Archaeologists using the time-scale terminology must be aware of this just as other Quaternary scientists involved in archaeology should know and understand the basic cultural chronologies they deal with. As in archaeological chronologies, the details of the time scale (e.g., specific definitions of time periods, ages of the boundaries) may not be agreed on. In such cases the criteria used or the conventions followed should be clearly spelled out. Depending on one's view of the Plio–Pleistocene boundary, miscommunication could make a difference of 800,000 ka or more (1.6 my vs. 2.4 my vs. 2.6 my for the age of the boundary), spanning a significant interval of human evolution (the end of the Australopithecines and the appearance of Homo; Kimbel, 1995). For the Pleistocene–Holocene boundary, most definitions vary by only a few thousand years at most (e.g., 11,000 yrs vs. 10,000 yrs), but those years span significant changes in environment and in culture worldwide (e.g., Eriksen and Straus, 1998; Straus et al., 1996).

Among the most distinctive characteristics of the Quaternary are global cooling and dramatic, cyclic environmental change. The most obvious and best known physical manifestation of these characteristics is the formation of huge ice sheets and the evidence for their repeated growth and decay. The record of Quaternary environments in general, and of glacial–interglacial cycles in particular, were long viewed fairly simplistically in the absence of extensive, dateable field evidence, but with the post–World War II growth of Quaternary research and methodology, this view changed. The deep-ocean record of ice volume and environmental changes revolutionized thinking about the Quaternary. Moreover, the ocean record provided a standard scale and terminology for correlation and comparison of Quaternary events.

The record from the ocean and the complexities of the terrestrial stratigraphic records have now been known for over a quarter century. There is no need to perpetuate the myth of the fourfold glacial sequences for the Midwest and for Europe and they should be excised from texts, archaeology and otherwise (Fagan: 1992, Table 3.2; Hester and Grady, 1982, Table 6-1.) Some volumes on archaeology and even a few on geography still present the old glacial schemes, or both the old schemes and the new interpretations, and yet others suggest that the old, named glacial intervals are simply the most recent ones (e.g., Fagan, 1992, 1997:113, Table 3.2; Hester and Grady, 1982:105–107; McKnight, 1996, Table 20–1; Renfrew and Bahn, 1996: 119–120), which is both confusing and misleading. Most of the classic glacial stratigraphic terminology is largely outdated, if not hopelessly muddled, and some of the terminology is now abandoned (Bowen, 1978:10–56; Ehlers, 1996; Sibrava et al., 1986). As noted, for example,
in the midwestern United States only the terms for the more recent intervals are still retained (Wisconsin, Sangamon, and Illinoian; e.g., Hallberg, 1986; Johnson, 1986).

Working with proxy indicators presents several potential problems. A continuing problem is the lack of modern analogues for a number of plant and animal communities and for some geologic and geomorphic conditions found in Quaternary records (Rymer, 1978). This is particularly a problem for glacial periods and for the late glacial–postglacial transition. For example, certain mixed-conifer hardwood forests that existed in eastern North America in late glacial times have no modern analogues (Delcourt and Delcourt, 1987). Among mammal communities during full-glacial times, heterogeneity was greater, differing environmental gradients resulted in dissimilar species composition, and individual species shifted at different times, in different directions, and at different rates in response to late Quaternary environmental changes (FAUNMAP Working Group, 1996). Fluvial systems were significantly modified by greatly expanded ice sheets and permafrost regions, by different patterns of atmospheric circulation, and by drainage of huge quantities of glacial meltwater (Knox, 1995). Immense glacial lakes that once existed at the southern margin of the Laurentide and Cordilleran ice sheets produced huge catastrophic floods at scales unknown historically (Baker, 1997). The magnitude of the discharges were such that modern hydrological parameters may be insufficient for flood reconstructions (Baker, 1978). A related problem is that of evolution and extinction. “The frequency of climatic and environmental change during the Quaternary may have resulted in an acceleration in rates of evolution and of morphological characteristics compared with preceding geological periods” (Lowe and Walker, 1997: p. 230). This is particularly a problem with older fossil assemblages due to the higher proportion of extinct species and the increasing evolutionary distance from the modern equivalents (Kurten, 1968; Lundelius, 1976).

Interpretation of individual proxy indicators also have limitations and usually some problematic issues. None provides “The Truth.” Generally these issues fall into one of three categories: preservation, representativeness, and interpretation. Differential preservation can provide a biased sample. Pine pollen is much more resistant to degradation than pollen from other species, so high levels of pine pollen in a sample are not necessarily meaningful (Bryant and Hall, 1993). Likewise, pine trees produce pollen in massive quantities that can be distributed for tens to hundreds of miles downwind (Bryant and Holloway, 1983). What, therefore, do high levels of pine pollen in a sample mean? In contrast, phytoliths are deposited very close to the plants that produced them (Piperno, 1988:142–146). Dispersion, therefore, is not as problematic as in pollen studies, but phytoliths from plants in the bottom of an alluvial valley subject to fluctuating hydrological conditions may not be representative of regional conditions. Finally, what do biological and geological records and changes in the records mean? Are they indicators of effective precipitation or of absolute rainfall? Are there lag effects in geological and biological systems following a climate change, that is, do plant and animal communities and geomorphic systems respond to climate changes at different rates (e.g., Cole, 1990; FAUNMAP Working Group, 1996; Knox, 1972)? If the changes are synchronous, does the direction of change vary
depending on local and regional factors (e.g., Knox, 1983; FAUNMAP Working Group, 1996)? Ultimately, the best approach to solving or avoiding these problems is to use an array of proxy indicators in environmental reconstruction.

A number of problems and limitations warrant considerable caution in the utilization of outputs from GCMs, especially at archaeological scales of time and space. Most of the available results are from models that did not incorporate factors such as cloud cover or interactive ocean dynamics (Kutzbach et al., 1993:60–61; Street-Perrott, 1991). Cloud cover and ocean circulation have significant impacts on climate but for a variety of reasons are not yet part of most models. Street-Perrott (1991) also correctly pointed out another major criticism and concern: “a serious danger of circular reasoning if the same palaeoecological data are used both to specify the surface-boundary conditions and to test the model output” (p. 78). Street-Perrott (1991) also discusses several instances of “glaring discrepancies…between modeled climates and geological data” (p. 78; see also critiques of GCMs by Shackley et al., 1998, and Trenberth, 1997). For example, the models did not reproduce paleoclimatic conditions clearly evident from a variety of proxy data (e.g., Grayson, 1998). Also, because of their coarse spatial (continental to subcontinental) scale and because the experiments have been run for only a few simulated months, “it is unwise to place too much reliance on the regional details of the experiments” (Street-Perrott, 1991, p. 74). “GCMs…cannot be expected to predict what happened at a particular site. Instead, comparisons between model predictions and palaeoenvironmental data are best made by considering the general pattern of changes across a continent” (Harrison et al., 1991:236). Most field-based questions about past environments in archaeology and in other Quaternary sciences deal with much smaller spatial scales than can be modeled by GCMs (e.g., at the scale of an archaeological site or group of sites). Investigators must consider more seriously the applicability of a GCM to a single site or a small area such as a watershed, especially if these study areas are some distance from the grid points used in the model. Part of the answer will depend on the significance of local environmental factors such as slope, aspect, soil and rock types, and the local surface and subsurface hydrology.

Archaeoclimatic modeling has been able to reproduce records of climate change based on proxy indicators for a number of localities around the world with reasonable results (Bryson and Bryson, 1996, 1997b). Because the models are site specific and are intended for archaeological applications, they should and have generated considerable interest among archaeologists. The model results provide no linkages or explanations for climate trends (either in phase or out of phase, and based on either computer computations or proxy data) observed among a set of sites, however. This may limit some applications of this approach because contemporary archaeology tends to deal with problems beyond the level of individual sites. As with other climate models, the output is intended to provide testable hypotheses for further research. A continuing problem with all model results is reconciling differences between the field data and the model results. A rule of thumb applicable to any comparison of field or proxy data with data generated by laboratory analyses or computer-generated output is to rely on the field or proxy data.
A fundamentally important distinction between paleoclimatic reconstructions based on proxy records and those based on computer simulations (including both GCMs and archaeoclimatic models) is that the former are based directly on data whereas the latter are based on mathematical computations, that is, simplifications and generalizations. Too often the tendency seems to be to assume that because computer-generated models are expensive and run on very powerful computers, they must provide some sort of mathematical truth (e.g., Shackley et al., 1998). They do not. What they do provide are hypotheses regarding climate changes and climate patterns that can be tested using proxy indicators. Reconstructions based on proxy indicators are not tested against climate models; the proxy data are used to test the model results.

Several mechanisms appear to drive late Cenozoic environmental changes, and each operates at a different scale of time and space. Most of these probably had some effect on human prehistory. Sherratt (1997) is emphatic on this point: “Environmental change is not simply a backdrop to evolution: it is a principal reason for major episodes of biological change. It is no coincidence that successive species of hominid made their appearance during the Quaternary period, with its rapid pace and massive scale of environmental alteration” (p. 283)

The links between cause and effect are unclear, however, and in any event are not agreed on. The longer term changes such as the overall trend in late Cenozoic cooling and in glacial–interglacial cycles probably contributed to early hominid evolution. For example, Kimbel (1995) noted “a general correlation…between the late Pliocene onset of global climatic change and a net increase in hominid taxonomic and adaptive diversity over the period 3.0-2.0 myr.” deMenocal and Bloemendal (1995) were somewhat more specific, arguing that “If climate had a role in determining hominid evolution, the most parsimonious interpretation of the available data is that it was a change in mode of subtropical climate variability rather than a wholesale, stepwise change in climate that prompted evolutionary response.” (p. 284). Kimbel (1995) also noted, however, that “Of the three million years of hominid evolution…, about one-half of that time remains virtually undocumented” (p. 435). That is, the record of hominid evolution and hominid environments is substantially coarser, and for some time intervals is altogether lacking in comparison to paleoclimatic data from other regions and sources. In any event, “the hominid data base must improve considerably before we can move from proposing correlations to the meaningful testing of causally specific hypotheses” (p. 436).

The databases for the paleoclimates and the archaeology of later Quaternary time are significantly more complete and better documented than for the earlier Quaternary. A striking feature of late Quaternary human evolution is the “activity” in physical and cultural development compared to earlier times. Having passed through 30 or so glacial–interglacial cycles, the first “clear morphological evidence of cold adaptation” comes with the Neanderthals (Stringer, 1995, p. 530), and the diversity of modern humans comes only in the most recent cycle (e.g., Eriksen and Straus, 1998; Straus et al, 1996).

Probably one of the most archaeologically significant developments in Quaternary research is the discovery of evidence for very rapid (at the scale of human generations) and significant environmental changes during the last glacial
interval (oxygen isotope Stage 2) and perhaps in the Holocene as well. These changes are well documented in the Greenland ice sheet and in sediments from the floor of the North Atlantic, but their manifestation in terrestrial stratigraphic and archaeological records around the globe remains unclear. Nevertheless, the general correlation between the environmental “flip-flops” of this time and the dramatic changes in human dispersion, settlement, subsistence, technology, and art that took place as fully modern Homo sapiens lived during and emerged from the last full-glacial episode have generated considerable archaeological and paleoecological interest and research (e.g., the collections of papers assembled by Eriksen and Straus, 1998; Gamble and Soffer, 1990b; Soffer and Gamble, 1990, and Straus et al., 1996).

Several significant issues must be resolved in order to understand better the relationship between the various environmental changes of the late Pleistocene and Holocene and human physical and cultural evolution, however. Adequate age control is generally not available from most localities to document environmental shifts occurring at the same rate as the onset of the Younger Dryas and other rapid environmental shifts, and several “plateaux” occur in the radiocarbon calibration curves for this time (Stuiver and Braziunas, 1993), further hampering correlation (e.g., Bar-Yosef, 1993:517–519). Moreover, a remark by Kimbel (1995) with regard to early hominid studies is equally applicable here: the “data base must improve considerably before we can move from proposing correlations to the meaningful testing of causally specific hypotheses” (p. 436).

More broadly, some human adaptations probably were directly related to Quaternary environmental fluctuations, some undoubtedly were not, and many probably were complexly interwoven with both environmental and nonenvironmental forces (e.g., Butzer, 1982; Gamble and Soffer, 1990a; Sherratt, 1997; Wobst, 1990). An important step in dealing with this issue is the recognition of the varying spatial and temporal scales of environmental change (Butzer, 1982:23–32; Gamble and Soffer, 1990b:8–12). A related issue is assessing the linkage, if any, between specific environmental changes and the archaeological record (e.g., Meltzer, 1991; Sherratt, 1997). “[A]lthough the biophysical evidence leaves no doubt as to repeated environmental changes of different amplitudes and wavelengths, there is no archaeological case for causally related technological or behavioral readjustments” (Butzer, 1982:301). “Human adaptations, at whatever wavelength of climate cycle, need to be assessed in terms of organization rather than simply as a set of technological solutions” (Gamble and Soffer, 1990b:12). Searching for and sorting out these various relationships and linkages is one of the most important, daunting, and exciting areas of research for archaeologists and for other Quaternary scientists.

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