RECENT DEVELOPMENTS IN QUATERNARY PALEOCLIMATOLOGY

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ABSTRACT. Sources of paleoclimatic data for the Quaternary have greatly increased in the last twenty years. Long terrestrial records, in ice cores, lake sediments, peat and loess-paleosol sequences have greatly expanded knowledge of climatic changes over the last interglacial-glacial cycle; the reconstruction of past atmospheric composition has been of particular significance. Developments in dating methods (accelerator-based ^{14}C, thermoluminescence [TL] and electron spin resonance [ESR] dating) have been important in understanding the paleoclimatic record in sediments. New techniques are needed for recovering deep ice cores from ice sheets and long cores of lacustrine sediments in order to expand the limited number of terrestrial records which cover the last interglacial-glacial (and earlier) cycles.

INTRODUCTION

Twenty years ago, the record of past climate was primarily based on continental deposits, but these were rarely continuous sedimentary records and so the picture of climatic variations which developed was consequently incomplete. In the next decade, studies of marine sediments revolutionised our understanding of climatic variations and enabled models of the causes of climatic change to be tested. Extensive sampling programs for marine sediments also provided a global perspective on the observed changes (CLIMAP, 1976; 1984). Undoubtedly, studies of marine sediments provided an explosion of information which has continued to grow in quantity and quality (Ruddiman, 1985). However, the last ten years have seen a renewed focus on continental records of climate which complement the perspective provided by marine sediments (COHMAP, 1988). Continental deposits often provide more detailed information about short-term (high frequency) changes of climate than most marine records, raising new questions about the causes of climatic variations and feedbacks within the climate system (Broecker et al., 1986).

During the last decade much research has focused on the role of carbon dioxide (and other 'greenhouse gases') in the energy balance of

A. Berger et al. (eds.), Climate and Geo-Sciences, 165–171.

the earth-atmosphere system. Of critical importance has been the need to provide a long-term perspective on natural CO_2 variations prior to any anthropogenic effects. Studies of ^{13}C in planktonic and benthic foraminifera provided the first view of how CO_2 concentrations might have varied in the distant past, over an interglacial-glacial cycle (Shackleton et al., 1983; Pisias and Shackleton, 1984; Shackleton and Pisias, 1985). CO_2 levels were significantly lower in glacial times, and as high as, or higher than, Holocene levels in the previous interglacial. In broad outline, this view has been confirmed by studies of air trapped in ice from Antarctica (Barnola et al., 1987; Neftel et al., 1988). CO_2 concentrations of only 180-200 p.p.m.v. characterized the last glacial maximum as well as the preceding glacial maximum (marine isotope stage 6). However, there are important differences between the ice core and marine sediment-based reconstructions of former CO_2 levels which point to new and potentially significant lines of future research.

In addition to the CO_2 studies in ice from Antarctica, equally important parallel studies of $\delta^{18}O$ and δD have enabled paleotemperature estimates to be made (Lorius et al., 1985; Jouzel et al.,1987). Comparison with the CO_2 record suggests that orbitally-induced radiation changes are amplified significantly by interglacial to glacial CO_2 changes (Shackleton and Pisias, 1985; Genthon et al., 1987). This is an important development in the quest for understanding the causes and mechanisms of glaciation and deglaciation.

Ice cores have also provided fertile ground for studies of shorter-term climatic variations and of detailed measurements of past atmospheric composition. For example, studies of Antarctic ice indicate CO_2 levels in the mid-18th century averaged ~280 p.p.m.v. (Neftel et al., 1985) compared to 348 p.p.m.v. in 1987. A long ice core from Peru has provided a very important ~1500 year record from tropical South America where detailed paleoclimatic records are very sparse (Thompson et al., 1985; 1986). In particular, the Little Ice Age, from 1490 to ~1880 is clearly recognizable. More recently, the recovery of several cores from the Dunde Ice Cap on the Qinghai-Tibetan plateau (38°N, 96.4°E, 5300m) promises to provide very significant information about past climate and loess deposition in this area (Thompson et al., 1988). Other extra-polar ice caps in South America and Central Asia have the potential of providing detailed paleoclimatic records from areas about which very little is known. Efforts to recover such cores are likely to be extremely rewarding. In addition, new deep ice cores from Greenland will provide an important northern hemisphere data set for comparison with the Antarctic records.

Continuous continental records spanning more than the last interglacial-glacial cycle are extremely rare compared to those from the marine realm. Relatively few well-dated records exist. One of the most detailed records to emerge in the past decade is that of Hoochiemstra (1984) who studied in great detail pollen variations in a 357m core from a former lake basin in the High Plain of Bogota, Colombia (~5°N). This monumental study utilized radiocarbon, fission track, K/Ar and paleomagnetic reversals to provide a chronology of vegetation changes over the last 3.5 million years. These changes were then compared with the marine sedimentary record of paleoclimate (Hoochiemstra, 1984, 1988; van der Hammen, 1985). Hoochiemstra's study is unique; no other continental paleoclimate record exists which is so well-dated and which has been examined in such detail. Other long cores spanning the last interglacial-glacial cycle have been studied (e.g. Grande Pile: Woillard, 1978; Woillard and Mook, 1982; Clear Lake: Adam et al., 1981; Adam and West, 1983) but only a few lacustrine records exceed this time period (e.g. Lake Biwa: Fuji, 1979; Horie, 1987).

Regions of loess deposition, beyond the former margins of continental ice sheets, provide some of the longest and best paleoclimatic records from the continents. Alternating periods of loess deposition and soil formation are well-recorded in many areas (Pye, 1987) but the longest continuous records are from central China, spanning over 2.4 million years (Liu et al., 1985a, 1985b; Heller and Liu, 1982; Kukla, 1987a). Studies of soil, pollen and faunal remains have enabled paleoclimatic conditions to be estimated (Liu et al, 1985b). Until recently, dating was based mainly on a paleomagnetic reversal stratigraphy, but recent studies have supplemented this chronology with TL and amino acid age estimates. Variations in magnetic susceptibility also hold great promise for further defining the loess/paleosol chronostratigraphy (Kukla et al., 1988). Paleoclimatic interpretation and correlation of loess deposits from eastern Asia to western Europe (e.g. Kukla, 1987b) and from North to South America remains a goal for future research.

Dating of continental deposits remains problematical, particularly when examining short-term, 'abrupt' changes in climate (e.g. Woillard, 1979; Seret, 1983; Frenzel and Bludau, 1987). Tandem accelerator mass spectrometry techniques for ^{14}C have proven to be very useful in constructing detailed chronologies of paleoclimatic variations (e.g. Bard et al., 1987). Thermoluminescence (TL) and electron spin resonance (ESR) dating methods have received much theoretical and experimental attention over the last decade and their application to dating sediments such as loess (at least over the last interglacial-glacial cycle) has been an important development (Wintle and Huntley, 1982; Wintle, 1987; Hennig and Grun, 1983; Radtke and Grun, 1988). Recent developments in optical dating of sediments suggest that this will also become a useful technique (Huntley et al., 1985; Godfrey-Smith et al., 1988).

^{10}Be measurements in ice cores (Yiou et al, 1985) and in loess (Shen, 1987) have provided a very important new method of checking the chronologies of continental deposits. Further work on the long-term flux of ^{10}Be is an important area of future chronological research with direct significance for paleoclimatology.

Computer models of the general circulation (GCMs) have been employed more frequently in the last decade to examine changes related to orbital forcing and differing boundary conditions at various times in the past (Kutzbach, 1985; Crowley, 1988). Models have also been used to simulate $\delta^{18}O$ and desert dust dispersal during glacial time (Joussame and Jouzel, 1987). Comparison of model output with paleoclimatic records provides a basis for placing sparse proxy records into a global perspective and for checking both the accuracy of the model reconstructions and of the interpretation of proxy data (e.g. Kutzbach and Street-Perrott, 1985; Kutzbach and Wright, 1985).

The last decade has witnessed important developments in paleoclimatology, particularly with respect to records from the continents. However, since most climate proxies are sedimentary deposits, in which material from one moment in time is buried by ever-younger sediments, reconstruction of past climate must begin by recovering a well-preserved sedimentary record. This seemingly trivial problem is, in fact, a significant barrier to future paleoclimatic research. For example, the technological problems of recovering a high quality ice core from depths exceeding 3500m in East Antarctica are quite profound. Similarly, many potentially valuable lake sedimentary deposits await the development of coring devices which can be deployed with minimal logistical problems in what are often relatively isolated locations. Analytical techniques and laboratory facilities are already available to examine the materials recovered. With improvements in the technology of core recovery, the prospects are excellent for obtaining many new continuous continental climatic records spanning the entire Quaternary.

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