Continental Drilling for Paleoclimatic Records

Recommendations from an International Workshop

GeoForschungsZentrum, Postdam, June 30 - July 2, 1995

Sponsored by the GeoForschungsZentrum, Postdam, Germany
in conjunction with the International Continntal Drilling Programme (ICDP)

Edited by Steven M. Colman

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1. DESCRIPTION OF THE WORKHOP

1.1 Meeting Description

The Workshop, entitled "Continental Drilling for Paleoclimate Records", was sponsored by the Past Global Changes (PAGES) Project, a core project of the International Geosphere-Biosphere Programme (IGBP) and by the GeoForschungsZentrum, Potsdam, Germany, in conjunction with the International Continental Drilling Programme (ICDP). The impetus for the meeting was the need for long continental paleoclimate records that will fill gaps left by the marine and ice-core records and provide information on time and spatial scales that are relevant to human activities. Further impetus came from a perceived need to balance the forecasts and reconstructions of climate models with information on actual behavior of the climate system on the continents. The meeting was organized by Steven M. Colman, Suzanne A.G. Leroy, and Jörg F.W. Negendank and was held at the GeoForschungsZentrum, Potsdam, Germany, June 30-July 2, 1995. Because the Workshop was primarily a working meeting, a relatively small number of participants were invited (Appendix 3). Leaders of the PAGES Pole-Equator-Pole (PEP) transects and existing large-lake drilling programs, along with a mixture of technical experts, were the primary group of attendees.

1.2 Agenda

`Friday, June 30`
Opening Presentations
J. Negendank: Welcome, introductions, and workshop logistics.
I. MacGregor: Opening Address: The International Continental Drilling Program and Continental Paleoclimate records.
S. Colman: Objectives and Products of the Workshop

Presentations by Program/Agency Representatives
M. Fratta: The European Science Foundation and continental paleoclimate records.
H. Zimmerman: PAGES perspectives and research needs in continental paleoclimate records.

Case Histories of past and present drilling/coring projects
T. Johnson: International Decade of East African Lakes (IDEAL)
J. Negendank: Development of the European Lake Drilling Program (ELDP)
H. Hooghiemstra: Bogota Basin Drilling Project
T. Liu: Drilling for paleoclimate records in China
T. Ager: Yukon Basin Drilling Project
D. Williams: Baikal Drilling Project (BDP)
M. Saarnisto: Cooperative Finnish-Russian Lake Coring

`Saturday, July 1`
Working group meetings, Session 1
Working group meetings, Session 2

`Sunday, July 2`
Working group meetings, Session 3

Open Discussion
Reports of working groups and discussion
Strategies for implementation of recommendations
The Workshop Report

1.3 Working Groups

Three sessions of each of the three working groups allowed workshop participants to rotate among each of the three groups. Only the discussion leader and the recorder stayed attached to one working group, for coordination and reporting. The following outline reflects the charges given to each working group.

WORKING GROUP 1. Scientific objectives and planning

Discussion leader: T. Johnson
Recorder: T. Ager

1. What are the primary objectives, questions, goals related to continental drilling for paleoclimate?
For example:
· Records to complement those from ocean and ice cores in order to provide truly global reconstructions
· Regional variation of past climates
· Impacts of climate change rather than just change itself

2. What kind of sites should have highest priority?
Emphasis to be placed on discussion of criteria, such as:
· Major areas where paleoclimate data is lacking
· Areas of special sensitivity or critical for answering specific questions
· Continuity, length, and resolution of record
· Present-day deposition (for calibration)
· Dating potential
· Multiple and (or) quantitative proxy potential

3. What structure and procedure are needed for effective planning and organization?
For example:
· Chief Scientist, steering committee, sampling committee, data manager
· Pre-proposal organization meeting(s)
· Recruitment of participants for different dating and proxy analyses
· Written agreements among participants
· Prior information needed about a site; planning for "site survey" or reconnaissance stages
· Selection of drilling equipment; logistics planning

WORKING GROUP 2. Drilling and post-drilling operations and technology

Discussion leader: J. Negendank
Recorder: J. Magee

1. Drilling technology
· What kinds of drilling equipment are appropriate for different scales and types of records and analyses?
· What procedures are necessary to insure recovery of the highest possible quality of cores (duplicate cores/holes, use of liners, re-entry procedures, drilling log records)?
· What down-hole, post-drilling measurements are most useful?
· Recommendations for transportation and short-term storage
· Technology for special circumstances, including portable equipment for remote areas, and technological developments needed to drill large, deep, unfrozen lakes

2. Pre-sampling protocols: What kinds of facilities and coordination are needed? What are the criteria for deciding where cores will be stored?

· Whole-core, non-destructive measurements (e.g. magnetic properties, GRAPE, P-wave velocity)
· Post-splitting, pre-sampling activities (description, photography, X-ray)

3. Recommendations for storage and archiving of cores

WORKING GROUP 3. Sampling, analytical, and data protocols
Discussion leader: F. Gasse
Recorder: M. Duvall

1. Analytical protocols; protocols for individual analyses adapted from PALE and IMAGES documents

· Emphasis on multiple proxy and dating methods
· Who performs and who coordinates sampling?
· How sampling conflicts are to be resolved
· Access to samples by non-project researchers; time table for tiers of exclusive use; core preservation as a long-term resource

2. Data Dissemination and Management

· Data exchange among participants
· Data management during analytical phase
· Data distribution outside the project
· "Permanent" data archiving and public access

3. Publication protocols; responsibilities and guidelines to avoid problems such as precedence and "skimming"

· "Initial results" reports
· Use of data by other investigators
· Publication of analytical or topical papers
· Publication of summary papers

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1. DESCRIPTION OF THE WORKSHOP

2. INTRODUCTION

The impetus for this Workshop came from a growing need for long continental paleoclimate records within the Past Global Changes (PAGES) Project of the International Geosphere-Biosphere Programme (IGBP), together with the development of the International Continental Drilling Program (ICDP) and its Earth History and Climate Theme. In particular, the needs of the continental-scale, pole-equator-pole (PEP) transects of PAGES for long, high-resolution climate records provided a strong incentive for the Workshop.

Progress in global change research has come from many fronts in recent years. Much better understanding of the processes involved in the earth's climate system is now available, but along with this understanding has come a renewed awareness of the incredible complexity of the system. Much attention is deservedly given to climate-simulation models, most recently coupled ocean-atmosphere models, because of their ability to forecast. Such models, however, are just beginning to produce realistic simulations of human impact on the climate system that are comparable to those observed in the instrumental record (e.g. Santer et al., 1996). In addition to difficulties with accurately representing climatically important processes, models have problems in dealing with non-equilibrium conditions and non-linear responses. The record of the past shows that climate is constantly evolving, that "equilibrium" is relative to time scales, that sudden and unexpected events occur, and that earth systems may have internal, non-linear properties (such as "mode switches" in oceanic circulation). Thus, even as our understanding of climate processes grows, and our ability to model those processes increases, we are more dependent than ever on the record of past climate changes for true understanding of the climate system.

Finally, as important as it is to reconstruct climate changes of the past and to forecast them for the future, ultimately, it is the impact of those changes that are important to humanity. The continental paleoclimate record provides evidence of the impacts of past climate changes that are on a spatial and temporal scale that is relevant to human activity.

A wide variety of archives of continental paleoclimate records exist. These include historical records, tree rings, ice cores, relict geomorphic features, and sediments. The scope of the Workshop was restricted to records from sediment archives. Although records from all types of continental sediments are valuable and were considered within the scope of the Workshop, attention focused on lake sediments, because of their relative continuity, time resolution, and sensitivity to climate change, and because of the general ability to compare ancient lake sediments with their modern counterparts in the same lake. However, most of the discussion that follows applies to other continental sedimentary records as well, such as continuously accumulating loess in China.

0. TABLE OF CONTENTS 3. RATIONALES & OBJECTIVES

2. INTRODUCTION

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3. RATIONALES AND OBJECTIVES

Long, high-resolution cores are clearly one of the fundamental observational requirements for paleoclimatic reconstruction. Particularly useful are long cores obtained by drilling methods. Such cores have been obtained in many different environments, but the results of studies based on marine and ice-sheet cores have been particularly visible and influential in paleo-science. Because climatic records from the continents provide critical information for the complete reconstruction of the Earth's environmental history, and because continental climatic changes are most pertinent to human activities, it is essential that long, high-quality paleoclimate records be retrieved from terrestrial locations.

Typical drilling projects aimed at recovering continental paleoclimate records have been conducted on an ad-hoc basis. Many such projects are supported by national funding sources and in many cases they produce valuable data and interpretations. From a global or international perspective, however, the aggregate of these projects appears to be poorly coordinated, and to be inefficient or redundant with respect to personnel, equipment, core archives, and sample analysis. This may be related partly to scientific culture, national funding structures, or independence from the need for large share-use facilities, such as those required for ocean or ice-sheet drilling projects. The situation is likely to continue; individual projects will develop and use their own drilling equipment and analyze cores for specific purposes. Only in the case of large, deep lakes (e.g., Lake Baikal and the East African Lakes) is the need for large-scale technology and facilities likely to provide enough impetus for coordination among large groups of researchers.

In the case of lake sediments, paleolimnology developed separately from paleoceanography, partly because of the diversity of lakes and their distinct depositional environments. Hence, many researchers focused on their own specific sites, rather than on broader correlations. Cores typically became exclusive property of one scientist, and analyses commonly were limited to those performed in their own laboratory. Cores of differing standards and sizes were subject to limited analyses for immediate needs, were rarely archived properly, and were commonly discarded. Problems related to lakes, such as unusual physical and biological limnology, endemism of taxa, unique depositional environments, and inaccurate bulk radiocarbon dating have discouraged long-range correlations. Most lake cores cover a relatively short period of time, commonly post-glacial, Holocene, or less.

For these reasons, PAGES would like to provide a framework for developing more organized and coordinated research on long continental paleoclimate records for the global-change community. Recommendations associated with this framework will serve as a set of guidelines or a "template" for continental drilling projects aimed at recovering paleoclimatic records.

These guidelines will provide:
1) a basis for evaluating proposed drilling projects by scientific organizations and by funding agencies,
2) incentives for advance planning and coordination,
3) support for the scientific synergy that emerges from large, interdisciplinary projects,
4) a basis for comparison of continental paleoclimate records.

Additional objectives of the workshop were to:
1) develop strategies for organizing drilling projects,
2) consider ways of developing technology related to continent-al drilling,

3) encourage national support for drilling projects aimed at global change objectives.

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3. RATIONALES AND OBJECTIVES

4. SCIENTIFIC IMPORTANCE OF CONTINENTAL PALEOCLIMATE RECORDS

4.1 General Considerations

Considerable knowledge about past global climates and environments has been acquired in recent years, especially from deep sea cores and from ice cores taken from glaciers in Antarctica, Greenland, and smaller, low-latitude icecaps. Continental records obtained by drilling in lakes and filled lake basins have also contributed to understanding Earth's climate and environmental history. Most of what we know about the history of continental environmental changes is derived from analysis of glacial terrain, arid region landforms and other geomorphological features, and relatively short records obtained by coring trees, lakes, and bogs. These records have proved their value by providing important insights into how global and regional climatic events influence continental ecosystems upon which humanity is most immediately dependent. Compared to those from many marine cores, records obtained from the continents often provide direct evidence of past events on a local or regional scale, with relatively high temporal resolution.

Click on the graph for full size view

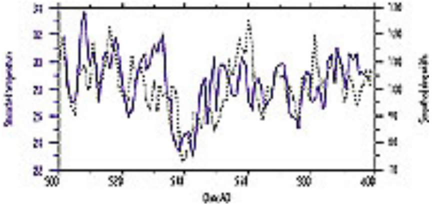

Figure 1.
Example of non-lacustrine, continental paleoclimate record , Time Stream I (0-2,000 yrs).
European oak index (dotted line) and Fennoscandian pines (temperature index, °C, solid line), which record an abrupt cold event at AD540, just before the outbreak of the Justinian plague in 542. It is likely that cold conditions caused widespread crop failures leading to famine and plague.
Figure provided by M. Baillie; Fennoscandian data courtesy of K. Briffa.

Continental paleoclimatic records are available from a wide variety of archives, including high-altitude ice cores, tree rings, relict geomorphic features, and many types of sediment, including loess and lake deposits. Lake sediments have many advantages over other types of continental archives, including:
1) their wide geographic and environmental distribution,
2) sedimentation that is commonly rapid and continuous,
3) the fact that lacustrine sediments can be directly compared to their modern counterparts in the same lake, which in turn can be compared to historical and instrumental records for calibration of climatic signals.

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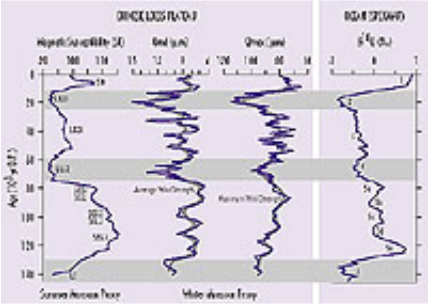

Figure 2.
Example of non-lacustrine, continental paleoclimate record, Time Stream II (ca.0-250,000 yrs).
Magnetic susceptibility and grain-size records from the Chinese loess plateau (Luochuan) as indicators of summer and winter monsoons, respectively (from Xiao et al., 1995).

4.2 Models and Mechanisms of Climate Change

Climate models have a need for increasingly reliable reconstruction of paleoclimate. High-resolution paleoclimate records from lake sites are still rare; methods of analyses have been inconsistent, processes poorly understood, spatial and time resolution is poor, and telecorrelations among a global network of sites almost non-existent. Groups promoting paleorecords stress the untapped importance of long and short time series from integrated studies of continental records, particularly if they are annually resolved (e.g. Oeschger and Eddy, 1989; Eddy, 1992; Bradley, 1991; Johnson, 1993; PALE Steering Committee, 1994; PAGES, 1995; (PANASH)).

A global network of lacustrine paleoclimate records can be used to establish boundary conditions, record rates of environmental change, and document ecosystem responses to those changes. A well conceived network of continental sites would provide independent tests of general circulation models (GCM's) of the oceans and atmosphere. As part of this global network, databases of specific limnological properties such as lake level (Guiot et al., 1993; Harrison, 1989; Harrison and Digerfeldt) are important.

The transient behavior of abrupt climate changes can be documented on the scale of human generations, but the mechanism forcing such events is largely unknown, except that the surface ocean is probably involved. Partly this is due to a lack of global data. For example, controversy about the structure of the Younger Dryas cold period (11,000-10,000 14C yrs B.P.) centers on a regional mechanism in the North Atlantic (cf. Broecker, 1994). This has spawned a world-wide search for time equivalent signatures. On the other hand, while attention focuses on abrupt changes during deglaciation, ice cores also reveal a tranquil Holocene temperature history. This contrasts with as yet unexplained observations such as rapid Holocene shifts in tropical water budgets and European lake levels. These are likely related to thresholds in monsoon systems, possibly in concert with changes in El Niño-Southern Oscillation (ENSO) behavior. Palynological transects through these contrasting areas, for example from northwest Europe through the Mediterranean to tropical Africa, are needed to decipher the regional signatures of these changes.

Multiproxy lacustrine records are contributing unique information on environmental change in space and time, and are providing goals for subsequent research in oceans and on glaciers. The records from several lakes in north and east Africa, for example, have identified major drying events in the Holocene at 8 ka and 4 ka that provide important insight into past behavior of the Intertropical Convergence Zone (ITCZ), an important component of the global atmospheric circulation system. This has inspired a search for evidence of subtle but important changes in marine records that correspond to the 4 and 8 ka horizons. Palynologists analyzing lacustrine sequences in the tropics of Africa and South America concluded years ago that these regions were 4-5 °C cooler during the last glacial maximum (LGM) than today. However, this conclusion is only now being seriously considered by the paleoceanographic community (Broecker, 1996) after new studies of varved marine basins (Hughen et al., 1996) and isotopic analyses of Peruvian glaciers (Thompson et al., 1995). It is, moreover, consistent with reconstructions derived from noble gas rations in low-latitude groundwater bodies (Stute et al., 1995).

4.3 Spatial Dimensions and Scales

Spatial resolution in reconstructing past environments, especially over the topographically complex continents, is an important factor in understanding how the climate system operates and affects the terrestrial component of planet Earth. To define climate dynamics, several sites over a region must show synchronous changes or closely related temporal trends. Paleorecords from continental archives do not resolve global paleoclimate in the same manner as ice cores, for example, which sample the Earth's atmosphere directly. Instead, they must be studied as archives which store the response of regional ecological and hydrological systems to climate change forcing. Lakes in many parts of the world offer the potential for providing the spatial resolution required for reconstructing the regional scale effects of climate change. Comparison of paleoclimate records from different types of lakes in diverse climatic and vegetational zones are required to fulfill this potential.

Long records from lake sediments are an underused archive that fill a gap in the global coverage of paleorecords. Ice cores are limited to polar regions and high-altitude ice caps. Tree rings are time-limited and are most useful across temperate latitudes. Lake sediments record the information in a variety of components that indirectly represent the atmosphere (precipitation, seasonality, temperature, variability, wind, storms, drought), the terrestrial ecosystem (pollen, insects, other fossils, organic matter, fire recurrence, volcanic ash events, flood recurrence, soil development, weathering) or the aqueous system (salinity; composition; evaporation; circulation and mixing; microbial, algal, and fish biota; aquatic plants; productivity; endemism; chemical sedimentation; organic matter; environmental isotopes; and others).

Lakes are widely distributed on the continents and come in a large selection of sizes, depths, chemistries, salinities, origins, and settings. Lacustrine freshwater giants such as the 70,000 km2 Lake Bonneville, may dwindle to hypersaline pools such as the Great Salt Lake, within a few centuries. Such transitions may be documented in only centimeters of sediment. Crater lakes capture rain like giant pluviometers monitoring the atmosphere, whereas other types of lakes such as shallow Lake Eyre, Australia, integrate the evolution of surface and groundwaters across half a continent.

4.4 Time Scales and Age Resolution

Lacustrine records usually can provide the temporal resolution of relevance on human time scales (Duplessy and Overpeck, 1996). Because of relatively fast sedimentation rates encountered in many lakes, opportunities exist to calibrate the sediment record of the past one to two centuries directly against historical and instrumental records of environmental change. Moreover, rapid sedimentation rates allow for quantification of the rate of abrupt environmental change. High-resolution records on the continents derived from lake sediments, for example, frequently show evidence of cyclic behavior with periodicities ranging from a few years to a few decades or centuries. While their existence and significance are still being evaluated, they offer the potential for providing new insights into the importance of processes such as ENSO and solar variability on global climate at time scales of immediate relevance to humankind. Although high resolution is possible for any length of lacustrine record, high-resolution methods are particularly needed for all or critical parts of long (> 250,000 yrs) records.

Annually laminated lacustrine sediments (varves) are part-icularly important for reasons ranging from the exact timing of clim-atic changes (e.g. Hajdas et al., 1995; Watts et al., 1996) to calibration of the radiocarbon time scale (Stuiver et al., 1991). Varves contain a wealth of annually resolved paleoenvironmental information (Anderson and Dean, 1988). Not only do records from such sediments address questions of inter-annual climate variability, but in some cases, they reveal details concerning seasonal changes (e.g. Zolitschka and Negendank, 1996).

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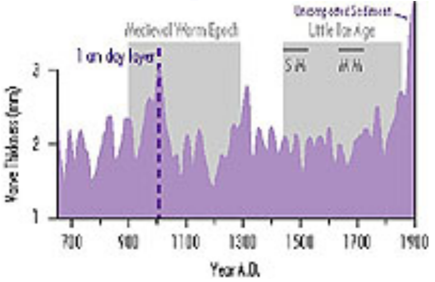

Figure 3.
Example of lacustrine paleo-climate record, Time StreamI (0-2,000 years), varve thickness record from Elk Lake, from Anderson (1993).

SM: Sporer Minimum
MM: Maunder Minimum

Where non-varved lake sediments are deposited at relatively fast and uniform rates, they document changes on time scales of decades to centuries. Radiocarbon methods are typically used to achieve this level of age control; where sedimentation rates are sufficiently uniform, time resolution can exceed the nominal several-decades analytical precision of radiocarbon analyses. Decade to century-scale climatic changes are particularly worthy of study, because the mechanisms for such changes are commonly less well understood than those for longer-term climatic variation. Examples include continental drought cycles (e.g. Knox, 1985; Wright, 1992) and so-called Heinrich events (Bond and Lotti, 1995).

Long records from lakes offer the potential for determining onshore records of long-term climatic changes, such as those associated with cyclic variation in the earth's orbit (Milankovich cycles). Potential differences in response to orbital forcing between oceanic and continental climates are important aspects of the climate system that need to be understood. The difference between the Devil's Hole record (Winograd et al., 1992) and the marine oxygen isotope record (Imbrie et al., 1984) is an outstanding example. Lacustrine records that span several 100,000-yr climatic cycles are relatively rare compared to those for the post-glacial period. Long records from single sites also have the advantage of minimizing the effect of non-climatic variables on the cycle-to-cycle paleoclimate signal of climate proxies.

Some large lakes of tectonic origin (such as Lake Baikal, the East African rift lakes, and the Bogota basin) may preserve records that span millions of years; significantly longer than the longest ice-core records and rivaling some marine records. In addition to paleoclimate records, sediments in these lakes may provide information about tectonic processes, such as rift formation.

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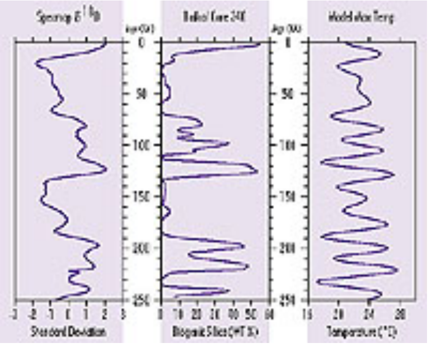

Figure 4.
Example of lacustrine paleoclimate record, Time Stream II (ca. 0-250,000 yrs).
Biogenic silica, a measure of diatom productivity, from Lake Baikal compared to SPECMAP oxygen isotope record and modeled maximum summer temperatures, from Colman et al. (1995).

On a longer time scale, regional environmental change caused by uplift of local or regional areas may be deciphered from several different environmental proxies. For example, uplift may block moisture-bearing air masses from penetrating as far into interior regions as they did prior to uplift, and be reflected in the composition of regional vegetation communities. Uplift may also affect rates of weathering, which in turn affect the global CO2 budget. Understanding such regional environmental change is important, because evidence of global-scale climate variability may be confused with or obscured by regional tectonic events.

4.5 Societal Relevance

In many cases, lacustrine sediments record the impact of climate change as well as the change itself. Responses of terrestrial ecosystems, the hydrological system, and landscapes to climate change are clearly one of the most important aspects of global change research, in terms of relevance to human activities. For example, recent research (Bradbury et al., 1993; Markgraf and Kenny, 1996) indicates that vegetation and lakes may actually respond much more quickly to climate change than has been assumed previously. Aquatic vegetation may even record seasonal limnological changes (e.g. Haworth, 1984; Simola et al., 1981).

Lacustrine records of past environmental change are especially useful for gauging environmental response to human impact (e.g. Hollander et al., 1992), and comparing this response to "natural" changes that occurred prior to significant anthropogenic forcing (so called "baseline" conditions). The potential exists for quantifying the integrated watershed system response to anthropogenic and climate forcing, in terms of local and regional vegetation, soil development, water chemistry, and aquatic biota. This is possible because lacustrine records often provide several quantitative, independent, environmental proxies that may be used for reconstructing these and other conditions. These proxies include plant micro- and macro-fossils, soil minerals, aquatic microfossils, and authigenic minerals.

Lacustrine records can provide valuable information on past variability not only in climate and vegetation, but also in geological hazards such as earthquakes and volcanoes. Earthquakes, for example, may trigger turbidites in an otherwise quiet depositional setting. Volcanic ash layers record past eruptions and can be examined carefully for any associated changes in aquatic microfossils, pollen, or other indicators of environmental change. It may be possible to discern the effects of eruptions on regional ecosystems and environments from evidence preserved in lake sediments (e.g., vegetation changes, water chemistry changes, changes in aquatic ecosystems, such as diatoms). When such catastrophic change occurs, the rapidity of the ecosystem response and rebound is important.

Continental records not only provide information about climatic changes on temporal and spatial scales that are pertinent to human activity, but they also document the impact of those changes on the surrounding environment. It is this aspect of global change-namely the regional response and threshold behavior-which is most difficult to estimate from global climate modeling, but which concerns populations and societies.

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4. SCIENTIFIC IMPORTANCE OF CONTINENTAL PALEOCLIMATE RECORDS

5. RECOMMENDATIONS

5.1 Planning and Advance Work

As described in the previous section, this report focuses on lacustrine records among other continental archives because of the geographic and environmental distribution of lakes and their relatively rapid and continuous sedimentation. Independent, multiproxy, climatic signatures in lacustrine sediments can be calibrated to historical and instrumental records.

Length, continuity, and time resolution are clearly each important criteria for good lacustrine records, but in many cases, trade-offs exist among the three. In particular, for a given coring or drilling capability, record length is inversely proportional to sedimentation rate, whereas time resolution is directly proportional to this rate. Fortunately, many lakes contain a variety of sedimentary environments, which in turn have a range of sedimentation rates, and thus record length and resolution.

Lakes and their sediments are sensitive to a wide range of environmental conditions. Hydrological sensitivity is perhaps the most prominent, whereby huge lakes may form or entirely evapor-ate during climatic changes. Other important types of sensitivity also result from factors such as proximity to major climatic or veget-ation boundaries that have moved repeatedly in the past, such as monsoon paths and ecotones). Paleoclimatic sensitivity also results from situations in which past climate changes produced major changes in latitudinally or altitudinally determined vegetation zones. Different types of sensitivity may or may not affect the physical and chemical properties of a given lake. The link between particular climatic proxies and climatic sensitivity of lakes is espec-ially important in designing continental paleoclimatic studies.

The quality of chronology will always be a limit on the value of paleoclimatic records. Uncertainties in dating lake sediments are significant, especially beyond the limits of radiocarbon methods (typically about 40,000 yrs). The scientific community needs to recognize the urgent need to develop or refine methods to improve dating of long continental records. Varves exist at some sites and may provide excellent age control, but most sites require additional approaches. Where tephras are present and mineralogically suitable, isotopic dating and fission-track methods may be useful, either directly on core samples, or by correlation to other dated sections. Magnetostratigraphy may also be useful for establishing age control of long records, but the presence of unconformities are difficult to establish by magnetostratigraphy alone. All reasonable approaches to dating must be considered. This is a critical problem that is a key element for interpretation and comparison of records and for developing new proxies.

The consensus of the working group was that most resources should be used initially to obtain many records of 100-300 m, spanning about two glacial-interglacial cycles, and with broad geographic coverage. This is the largest gap in our knowledge on a global scale. However, at some point serious consider-ation should be given to drilling a few key localities where there is the potential for obtaining unique, long records approaching the time spans of millions of years.

5.1.1 Site Selection Criteria

Site selection partly follows from the primary type of proxy signature being examined. Undisturbed, continuous sections are most common below about 20 m water depth (deeper in large lakes), below the depth of storm and wave reworking. Varved sediments mostly occur where bottom conditions produce anoxia. Some small lakes preserve records of local vegetation and watershed conditions. In others, such as crater lakes or lakes that occupy most of their drainage basin, a significant proportion of sediments is captured directly from the atmosphere, so that a more regional signal is recorded in their sediments. Sediments in large lakes contain signatures of aquatic systems that tend to integrate conditions over larger regions and minimize the effects of local perturbations. Larger and deeper lakes provide the opportunity for imaging with acoustic systems to guarantee continuity and representation of sedimentary environments, but require greater logistical investments. In some cases, paired nearby lakes of different size and character are advantageous for the contrast in information contained in their respective sediments.

Because of the great diversity of lakes, simple site-selection criteria are difficult to define.
However, using the general guidelines discussed above, the following criteria are suggested as the most important for setting prior-ities for lake drilling and coring:
· Potential for developing multiple proxies that can be quantified and that are sensitive to past environmental conditions such as hydrology, vegetation, and climate.
· Location that contributes to a wide geographic coverage of past continental environments, especially across climatic gradients and as part of the PEP transects.
· Potential for long, continuous records with appropriate time resolution (annual to decadal for time stream I and at least century to millennial for time stream II and beyond). Records that can be used for several time scales and resolutions are especially valuable.
· Likelihood of dating the cores by several independent methods.

5.1.2 Planning and Organization

One of the most serious deficiencies of many large coring and drilling projects is a lack of planning and pre-operational organization appropriate to the scale of the project. For large, multi-investigator projects, advance planning should include the following:
· An organizational structure, such as a chief scientist and (or) a steering committee.
· Coring location recommendations based on site surveys and reconnaissance data.
· Agreements with all principal investigators to cover the required analytical and dating work.
· Plans for collaboration with scientific institutions and scientists of host country, if applicable.
· Agreements (at least preliminary) with institutions and (or) contractors who will perform the actual drilling or coring operations.
· Arrangements for core storage and archiving.
· Plans for obtaining all necessary drilling permits, environmental impact statements, waste disposal permits, and the like.
· Preliminary protocols for sampling, analytical work, data management, publication, and authorship of reports.

An advance planning meeting of all the principal investigators in the project is highly recommended. Many of the points listed above can be discussed and implemented in such a meeting.

The size, scope, and type of project will determine exactly how these recommendations apply to individual projects. Obviously, the recommendations can be scaled back for smaller projects, but even for such projects, each of the recommendations should be considered.

5.1.3 Preliminary Site Surveys

Pre-drilling site surveys are another often-neglected part of the planning process. All available survey and core data that relates to the type of sediment, the availability of climatic proxies, and the dating of the sediments should be collected and summarized. Geophysical surveys, especially acoustic reflection profiles are particularly useful for all but the smallest lakes. These surveys require some investment and effort, but modern equipment has made such surveys easier and less expensive. For larger drilling projects, they are a necessary first step to identify promising sites that have appropriate stratigraphic sequences and depositional environments. Surveys are also necessary to show that sites have not been disturbed by slumping, erosion, or faulting, and are not unsuitable due to the presence of gas.

In most lakes, projects should plan one or more transects of cores and modern surface samples from shallow to deeper waters. Where deeper lakes are subject to turbidite underflows, acoustic profiling may often identify deep water rise morphology where uniform pelagic sections are sedimented. Often a composite section can be pieced together to gain longer age access (e.g. coring up a tilted fault block). Field sampling of watershed streams, sediments, and biota, as well as lacustrine surface sediments, are important for defining the modern geochemical systems and calib-rating various paleoclimatic proxies to modern conditions.

5.2 Drilling Technology and Operations

5.2.1 General Considerations

Discussion of operational issues and technology is focused on drilling from lake surfaces, because of the significant advantages that lake sediments offer for calibrating paleoclimate proxy signals from modern depositional environments. In some cases, active depositional sites of eolian and fluvial sediments have similar potential, but drilling at such sites is technologically much easier due to the fact that they are land-based. However, many of the recommendations in this and succeeding sections concerning operations, handling, and sampling of lake-sediment drill cores apply equally well to other types of continental sediments.

Because of the wide variety of types of lakes and character of lacustrine sediments, coring or drilling methods used must be tailored to individual situations. In the following discussion "coring" refers to single-entry, relatively short (<12-15 m) systems, whereas drilling refers to multiple entry systems that recover a series of core segments. Three variables are the primary determinants of the type of coring or drilling system that is appropriate: water depth, penet-ration of sediment required, and type of sediment.

Water depth imposes a variety of technical constraints on coring and drilling. From a technical point of view, the following water-depth classes are of interest:
1) 0 (dry lake bed), water table below surface;
2) 0 (wet lake bed), water table at surface;
3) 0-15 m;
4) 15-100 m;
5) 100-400 m;
6) > 400 m.

An additional consideration that is important for technical reasons discussed later is whether the lake is ice covered during the winter.

Sediment type also affects the type of coring or drilling system used and the depth of sediment penetration that is possible with any given system. Lacustrine sediments more than 15 m below the sediment surface are generally at a depth and degree of consolidation that requires drilling. Percussion types of coring devices or drilling are also commonly required for thick sand or gravel layers, chemically precipitated (indurated) sediments, buried soil horizons, and volcanic ashes.

Additional factors that affect the quality of cores include:
1) stability (heave and horizontal position) of the drilling platform, which is a compromise between three competing factors: stability, portability, and cost;
2) the presence of sand and gravel, tephras, or indurated layers such as paleosols or evaporite layers;
3) remote location, which affects many of the drilling logistics;
4) experience and competence of the drillers;
5) the presence of gas in organic-rich sediments-degassing commonly destroys sedimentary structures, and in extreme situations, may constitute a safety issue (ODP Technical Report 22; see Appendix 1);
6) overlying materials, such as outwash or till, that are difficult to core.

Commercial drillers tend to be oriented towards making holes rather than obtaining cores. The need for high-quality cores distinguishes commercial drilling from scientific drilling. A head drilling engineer who fully understands both the scientific aim of the project as well as the drilling techniques being used is extremely valuable. Scientific drilling operators or contract drillers with experience in scientific drilling are desirable.

In a large-scale drilling project such as those addressed here, the primary technological and operational consideration must be obtaining the drill core in as undisturbed a manner as possible, and preserving it in as close to its original condition as possible. It makes no sense to mount a large-scale effort, only to obtain cores whose quality is compromised. These considerations apply particularly to soft, near-surface sediments and to the methods used to recover deeper drill-core sections.

5.2.2 Coring and Drilling Equipment

Figure 5.
Different types of corers in use on Lake Michigan:
(Photographs by S. Colman)

Sutar box corer	Large diameter (10 cm) gravity corer	Kullenberg-type piston corer (12 m)	Alpine vibracorer (9m)

A wide variety of coring devices, used to sample the uppermost sediment section, are available. The most common include:
· Box corers: commonly recover <1 m; used to acquire large volumes of undisturbed surface sediments.
· Freeze corers: commonly recover 0.3-2 m; often acquires undisturbed surface sediments, somewhat more reliably than box corers in water-rich sediments (Pachur et al., 1984; Renberg and Hansson, 1993).
· Push corers, such as Russian peat corer and Livingstone piston corer (Livingstone, 1965; Wright et al., 1965; Wright, 1967, 1980, 1991): recovery highly variable depending on sediment type; sediment ordinarily extruded from core barrel or sampled from exposed surfaces.
· Gravity corers: commonly recover 1-5 m, but in some cases 12 m or more; sediment disturbance varies with design, but may be minimal. Sediment-water interface may be disturbed.
· Piston corers, such as the Kullenberg type (e.g. Kelts et al., 1986). Many systems are capable of obtaining cores as much as 15 m long; new systems approach 30 m. Upper portion of the sediment section

is commonly disturbed or lost; disturbance of lower sections is variable. Many systems use a small gravity corer, which may obtain a good surface sample, as a trigger or trip weight. Piston corers may or may not include a liner.

· Mackereth corer (Mackereth, 1958, 1969; Barton and Burden, 1979): commonly 6 m, but as much as 12 m recovery with minimal disturbance; requires relatively shallow water depths (but greater than length of core barrel) and pneumatic pressure. Liner not used, so extrusion required. Minicorer version (ca. 1 m) recovers undisturbed sediment-water interface.

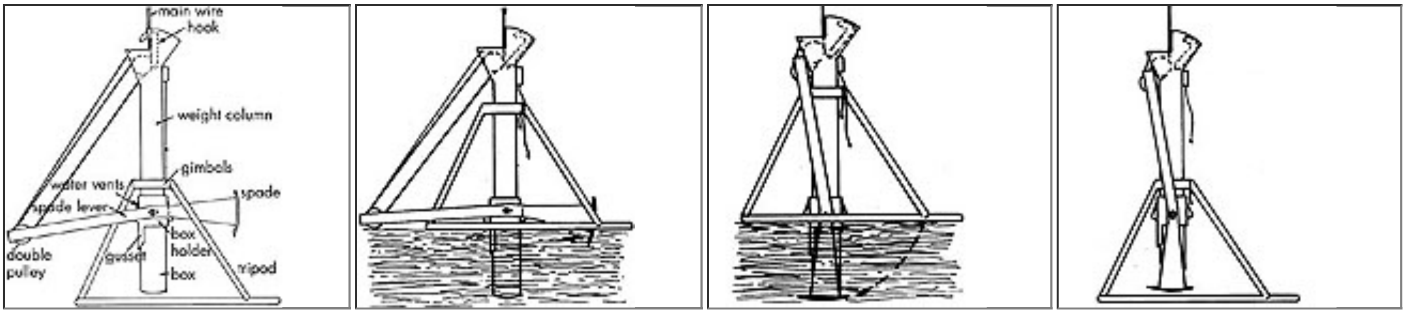
· Percussion corers, such as the Reasoner types (Reasoner, 1993): a variety of systems that hammer the corer into the sediment; sediment disturbance variable. Capable of penetration of sand and thin hard layers.

· Vibracores (vibratory, hydrostriker): recovery as much as 10 m; corer vibrated into sediment; sediment disturbance variable depending on design and sediment type, but may be minimal.

· Selcore: combination system using gravity, hydraulic pushing, and vibration, using pressure difference between the water surface and the lake floor.

Figure 6a.

Diagrams of box core operations, (modified from Rosfelder and Marshall, 1967)



1 descent | 2 penetration | 3 closure | 4 ascent

Several of these types of corers, especially Mackereth and vibracores, are capable of being configured to operate from a lake-bottom lander system. Deployment from the lake floor tends to increase reliability and minimize disturbance of the sediment core.

A wide variety of drilling systems are applicable to lacustrine sediments, including systems modeled on those of the Ocean Drilling Program (ODP), commercial drilling systems, and systems designed specifically for lake sediments. It is apparent that drilling and coring systems for continental drilling, especially in lakes, need to be much more flexible than ODP systems. Variations in lithology of continental sediments require multiple approaches, including hammering, percussion, vibration, and rotation. A list of drilling systems focused on lake sediments was compiled (see Appendix 2) and includes information on:

1) drilling and coring systems and techniques;
2) platform design and construction;
3) companies willing to work with scientists in developing specific techniques.

Commercial drilling systems may be useful for some continental drilling projects for paleoclimate research, if proper care and arrangements are made to maximize core recovery and quality. Core loss or disturbance from commercial drilling rigs usually results from failure to use a core liner (split-spoon or extrusion recovery of the cored material) or from vibrational or rotational disturbance from the coring tool itself. The latter type of disturbance is most severe for soft sediments near the top of the drill hole; other coring methods can often be used in combination with drilling to obtain a composite, minimally disturbed drill core. The use of core liners (thin, transparent plastic is most useful) is strongly recommended; a variety of wire-line, hydraulic, and hollow-stem-auger drilling systems can accommodate core liners.

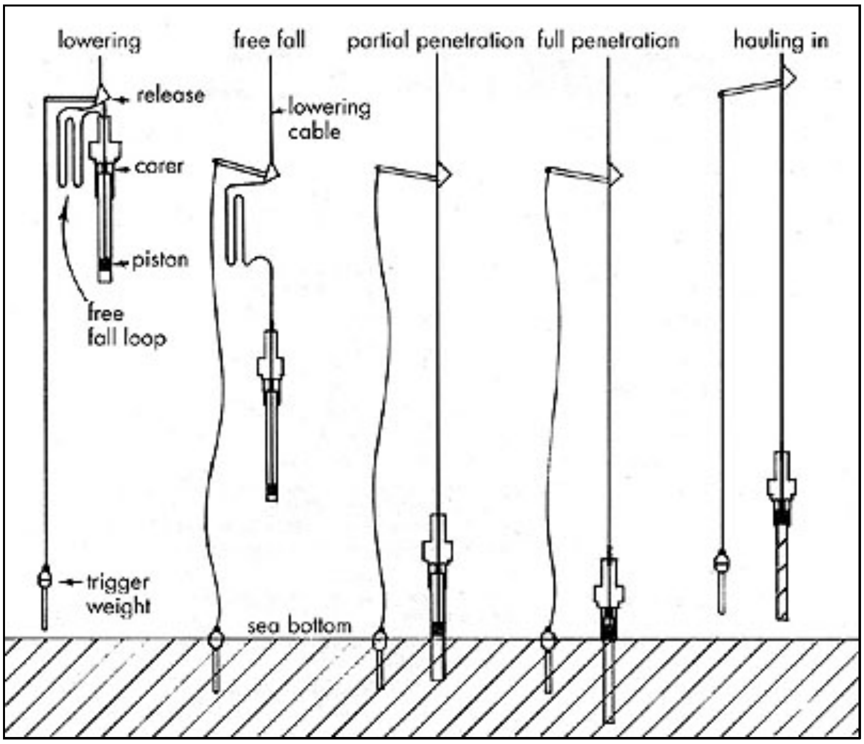


Figure 6b.
Diagrams of Kullenberg-type piston core
operations, (modified from Dixon and Karig, 1969).

New coring and drilling systems need to be investigated for use in lakes. An example might be modification of the drilling technology used for ice cores. Such a system would involve multiple re-entry (via a funnel shape at sediment surface) wire-line coring system. The corer would grip the hole sides by means of an expandable "packer". Hole stability and caving might be a problem and at least partial casing might be necessary. However, such a system might make 50-100 m cores significantly easier to obtain than is possible by present techniques.

The primary technological constraints on drilling oper-ations in lakes are related to the weight of the drill string and the stability of the drilling platform. The weight of the drill string is determined by the type of material (steel, aluminum) used, the water depth, and the amount of sediment penetration. This weight affects a variety of technical and logistical factors, including the size of the drill rig, the size of the drilling platform, the type of winch required, and others. For systems that use casing or a drill string, the drill rig must be kept in place over the drill hole. The positioning and stability considerations for such systems are discussed in the next section.

5.2.3 Drilling Platforms and Positioning

A variety of drilling platforms, from large barges to canoes, are available for drilling on lakes. The larger platforms, such as barges or sophisticated rafts, are expensive, but are necessary for large-scale operations. They can hold large drilling rigs as well as recommended support facilities, such as refrigerated containers.

For many lakes, portable, lightweight rafts are desirable because of access and logistical considerations. Catamaran-style construction is the simplest and provides a central working hole, which minimizes tilting problems. Rafts need to be repairable; modular cell systems are helpful. Aluminum is excellent for strength, weight and durability, but not as easily repaired (by welding) in remote locations.

Successful raft designs include:
1) the GeoForschungsZentrum system, which uses modular heavy-duty plastic cells that are bulky but light and strong, easily assembled, and very stable and buoyant; they are of Austrian manufacture and solve many of the problems associated with raft construction, but are quite expensive;
2) an aluminum frame system with inflatable buoyancy used by a South African group; this system is light

and small enough to be transported by air but is subject to problems of loss of buoyancy if holed and requires calm weather conditions;
3) the system of aluminum/polystyrene sandwich modules used by the Limnological Research Center at the University of Minnesota, which provides both construction strength and buoyancy.

In relatively small or shallow lakes, sufficient positional stability can be obtained by anchoring a raft or other platform, or by tying it to shore. However, the need to avoid significant heave may require calm weather. Heave is minimized by large platform size and by site locations with small wind fetch. In cold regions, thick winter ice can provide sufficient stability and platform capacity, either directly, or by holding a barge in position.

A major technological barrier exists for large, deep lakes that do not freeze solidly. The necessary platform stability for such lakes can be achieved by dynamic positioning, which typically keeps the platform in place over a transponder on the bottom. Robust, automatic systems such as that used by the ODP drill ship are very expensive and require deep water. To our knowledge, they have not been used in major drilling projects on lakes. However, simpler, manual, fair-weather systems are possible and can be very effective in the hands of a skilled operator.

Accurate site location can be established by using Global Positioning System (GPS) units. Simple, inexpensive receivers can achieve accuracy of less than 100 m, and differential GPS systems (using a second receiver fixed at a known location) can achieve accuracy of less than one meter.

5.2.4 Recovery Procedures

Virtually no drilling method can recover undisturbed cores of soft, near-surface lake sediments. Each lake-drilling project should thus include, for example, box cores, Mackereth minicores, and (or) freeze cores of the uppermost meter or so of sediment to provide material for calibration studies and to allow study of the most recent period of environmental change. Surface or core-top sediments are typically in high demand for such studies, and box cores provide the necessary large volumes of sediment. Depending on the drilling method used and the degree of consolidation of the sediments, the upper 3-10 meters of sediments should be sampled by multiple gravity or piston cores. As noted previously, efforts to recover undisturbed cores of the upper part of the section are relatively inexpensive and are critical to the overall success of a drilling project. Skimping on this aspect does not make sense.

Duplicate drill holes are recommended to cover gaps between core segments (segment depths should be staggered between the two drill holes) and to maximize the amount of mater-ial for analytical and dating studies. In some situations, more than two duplicate holes may be justified.

Several general procedures apply to many different types of drilling methods and serve to maximize core recovery and minimize core disturbance. They are slanted toward cased-hole, wire-line methods, but can be adapted to many other methods, such as hollow-stem augering.
· Use of casing wherever the stability of the drill-hole walls is in question (wherever sediments are less than fully consolidated).
· Coring drive should precede lowering of casing.
· If coring stroke is incomplete, casing drive should be adjusted accordingly.
· Drilling mud pressure should be carefully monitored to minimize disturbance while allowing material generated by the casing lowering to be flushed.
· Liners, preferably transparent plastic, in the coring tool are highly recommended.
· Multiple cores (multiple drill holes) are relatively inexpensive (because much of the drilling cost is associated with transportation and mobilization) and can be used to construct composite sections that solve problems such as coring gaps and gas expansion.

Complete and accurate drilling records should be kept for all aspects of the core recovery operation. These records should be a combined effort on the part of the on-duty drilling engineer and the scientist, and exact procedures should be agreed upon in advance. A variety of processes, including hole re-entry, incomplete recovery, compaction, and gas expansion commonly lead to uncertainties about the exact depths of recovered core sections. Uncertainty about which end of the core is the top is not unprecedented. Such depth uncertainties are critical to later correlation and time series analyses and need to be kept to an absolute minimum. Any other information related to the condition, treatment, or changes to core sections should be carefully recorded.

5.3 Post-drilling Operations

5.3.1 Transport and Short-term Storage

A number of procedures for storing cores at the drill site and transporting them to a permanent facility are recommended. The goal of these procedures is to keep the sediments as close to their original condition as possible:

· Cores should be stored in a dark, cool place (constant 4°C is recommended); this is strongly advised if cores are sealed in liners and essential if core materials are extruded.

· Refrigerated containers are recommended, if possible, for on-site storage and for transportation because of their availability, price, and portability.

· Strong magnetic fields and magnetic materials should be avoided during short-term storage and transportation in order to preserve the natural magnetic remanence and mineral properties of the sediment.

· If core sediments fill their liner or container, which is securely plugged and taped, they can be transported in any orientation. Water or cap space in the liner or container can be filled with styrofoam or similar material. If cores contain water, air, or gas, they should be transported upright and with extreme care.

· Because of likely subsequent disturbance during transport, cores should not be split in the field if it can be avoided. If cores must be examined in the field, local laboratories for permanent storage should be investigated. Some examination of samples in the field can be done on core-catcher or other disturbed material.

5.3.2 Storage and Archiving of Cores

Ideally, cores should be kept sealed in a dark, moist, and cool (4°C) location that is temperature and humidity-controlled. If the cores are in liners or similar containers, 1.0-1.5 m sections are convenient and can be sealed in plastic wrap or heat-sealed polyethelene tubing. Core sections can then be packed in more rigid and stable "D-tubes," along with saturated florists foam or other water-absorbent material. A computer data base of stored and archived cores is essential.

These procedures are designed to preserve the cores as close to their original condition as possible. In long-term storage, the largest disturbances come from drying and warming. Drying commonly destroys sedimentary structures, changes oxidation state, and modifies some mineralogy. Warming can lead to a variety of geochemical changes, dissolution or precipitation of carbonate materials, and microbial or fungal growth. Light also promotes algal and other growth.

5.3.3 Down-hole, Post-drilling Measurements

These procedures are generally costly and should be subject to cost-benefit analysis. They are probably necessary for important sites with long continuous records. Special large well-logging contract companies (e.g. Schlumberger) can probably only be considered for the deepest holes. For shallower holes (<500m) there are many smaller well logging companies which can provide relatively inexpensive services, even in deep-water situations. Down-hole logging can provide precise depth references of core segments.

Gamma logs are very useful as indicators of porosity and bulk density. Magnetometer, resistivity, and other geophysical logs of the drill hole also may be useful. Vertical, down-hole seismic profiles can be valuable, but they are expensive and difficult to perform under water. Down-hole video can also be very useful. Several other measurements can provide specific types of information that may be useful for paleoclimate studies (see ODP Technical Reports, Appendix 1).

5.4 Drilling Technology for Remote Areas

The sedimentary record of many of the lakes in the world are virtually unknown because these lakes are in remote areas where logistics and transportation are difficult. Examples of these areas include Siberia, tropical West Africa, and southern South America. Because lakes in many of these areas are the main source of paleoclimate records, they are especially important for implem-enting a global grid of paleoclimate sites. These sites are needed to establish regional patterns of climate changes, to document watershed responses to those changes, and to test climatic models. Thus, there is a strong need to develop drilling technology, particularly light weight drilling rigs, that can be transported and operated in remote areas. There is also a need for funding agencies to consider the additional transportation and logistic costs of projects in remote areas the same way they consider ship operating expenses in marine projects: as required components of scientifically valuable research.

5.5 Sampling and Analytical Protocols

Sampling and analysis of core materials is one of the most visible stages of drilling projects for paleoclimatic records, yet it is one in which problems commonly develop. The Ocean Drilling Program has developed elaborate procedures for these activities, and although they may not be directly applicable in all cases, they should be seriously considered for adoption or adaptation in continental drilling projects.

5.5.1 General Considerations

Most of the issues related to sampling and analyses, such as methods, priorities, sampling density, individual responsibilities, should be decided in advance of the drilling. Sample density will be partly determined by sedimentation rate and time resolution, and to the degree possible, these should be determined during preliminary site surveys. A reference list of sample priority should be explicitly developed and agreed upon.

So called "sampling parties," where all principle investigators are present, are recommended. Based on the results of all pre-splitting logging, imaging, and analyses, a core description and sampling strategy can be agreed upon. This process can be lengthy and must be well planned with equipment backups to minimize wasted time. However, once the basic strategy is established, sampling parties have proven very useful for discussion and consistency, and they enhance productivity and insight into the record through informal discussions among principal investigators. Although not essential, the use of a single, well equipped laboratory for initial core descriptions and measurements has considerable advantages. The use of such laboratories also facilitates sampling parties, which then can be held at the same location as all of the pre-sampling analyses.

A single material or sample coordinator for each project should be appointed at the proposal stage. The coordinator is responsible for resolving sampling conflicts, recording sampling activities, maintaining a priority list of samples for different scientific questions decided by the whole team, and for organizing sampling session(s). A single depth scale for a core is critical; it may seem like an obvious goal, but a variety of problems can lead to discrepancies in sample depths. Establishing and maintaining this depth scale should be the responsibility of the sample coordinator.

Standard analytical methods are encouraged, and standard reference samples for each analysis are important for evaluating the success of each analysis. Reference samples are absolutely mandatory when more than one investigator or laboratory performs the same analysis on a subset of samples.

Initial sampling should be planned at the highest level of resolution anticipated because of difficulties in resampling soft sediment, additional disturbance related to accessing cores multiple times, and other logistical problems. However, sampling may be divided into stages, such as primary and secondary stages, or reconnaissance and detailed stages, where appropriate. This procedure, along with secondary or duplicate cores, enables sequential interrogation of the record. However, definite schedules for multistage sampling should be agreed upon in advance to prevent disruption of the overall project schedule by delays in the results for individual analyses. Samples for different proxies should be taken at the same level, and the use of the same sample material in multiple analyses should be used where practical in order to preserve core material (see discussion of archive material).

Sampling priorities should be driven mostly by the scientific questions proposed by the project members as a group. For example, if river catchment history is a primary goal of the project, then the following analyses might have the highest priority: detrital-authigenic-biogenic ratios, X-ray diffraction mineralogy, organic carbon and palynofacies, sediment magnetic properties, and elemental analyses. For other project goals, other analyses might have higher priority. At the same time, some samples or measurements need to be taken or made immediately, before they are degraded or compromised. Examples include thin sections; photography; samples affected by oxidation processes (color, organic geochemistry, sulfur geochemistry, magnetic properties, and others), pore water chemistry, radiocarbon dating, and TL/OSL dating.

5.5.2 Individual Methods and Procedures

The following summary of methods is a skeletal guide to analysis of lacustrine sediments for paleoclimatic reconstruction. A detailed discussion of these methods is beyond the scope of this report, but the next section contains notes appropriate to the context of this report for each method, along with basic references that serve as a starting points for additional information. A wealth of other information about most of these methods is contained in the sources listed in Appendix 1.

Table 1: Recommended sequence and summary of procedures and analyses :

Column 2: Type

L, Logging; D, Description; A, Analytical; Dt, Dating.

Column 3: Required condition

Ideally, the sample requirements for each technique should be defined in terms of sample condition and sample size. Neither consideration is straightforward, and each varies with the technology used, especially sample size. For these reasons, only sample condition is considered here. Required condition assumes that proper pre-cautions have been taken to avoid contamination (e.g. air-born pollen). The following categories are useful, but do not accommodate every possibility.
1: Fresh, undisturbed, unfrozen, oriented (at least up and down).
2: Frozen as soon as possible after coring or sampling.
3: Fresh, undegraded required (r) or desirable (d); not frozen.
4.: Original volume measurement required (r) or desirable (d).
5: Dry mass measurement required (r) or desirable (d).
6: Bulk sample of undetermined original volume or mass acceptable.

7: Sieved residues acceptable.
8: Exposure to light or X-rays avoided.

`Column 4: Subsequent Condition`

These categories are related primarily to the degree of disturbance or destruction involved in the method. They have a strong bearing on the sequence in which analyses should be performed, and on which samples can be used for multiple analyses.

Whole core

A: Non-destructive, undisturbed. Whole core, preferably in liner, remains intact and undisturbed.
B: Non-destructive; invasive. As in (A), but limited sample or pore-water is extracted, commonly by a needle or probe through the core liner.

Split core

C: Undisturbed half core.

Core samples

D: Undisturbed. Samples remain in fresh condition with sedimentary structures and grain fabrics intact.
E: Fresh. Volumetric samples remain in fresh condition, but internal structures or orientation not preserved.
F: Dried. Samples remain in uncontaminated condition, but have been dried.
G: Fractions. Extracts, digests, or other fractions remain available for limited subsequent analyses.
H: Preparations. Thin sections, smear slides, and similar preparations possibly available for other analyses.
I: Destruction. Samples destroyed in analysis.

`Table 1: Recommended sequence and summary of procedures and analyses`

Method or Process	Type	Required condition	Subsequent condition
1. Magnetic susceptibility	L	1,5	A
2. GRAPE	L	1	A
3. P-wave velocity, resistivity, other logging	L	1	A
4. Sensitive geochemistry, (e.g. pore-water Eh-pH, O2; some C and S analyses)	A	1	B
5. Core splitting	D	1	C
6. Photography	D	1	C
7. X-ray imaging	D	1	C
8. Spectral/gray-scale scan	D	1	C
9. Thin sections	D	1	H
10. Smear slides	D	6	H
11. Visual descriptions	D	1	C
12. Bulk sampling, including sample splitting and mechanical size	D	3	D

separation			
13. Sediment magnetic properties	A	3, 4, 5	D
14. Bulk density, water content	A	4r	F
15. Organic geochemistry	A	2-3	I
16. Sulfur geochemistry	A	3	I
17. Organic Carbon and Nitrogen (± LOI)	A	5r	I
18. Granulometry	A	4	I
19. Elemental chemical analysis	A	4,5r	G- I
20. X-ray mineralogy	A	6	I
21. Sand/silt mineralogy	A	7	H
22. Carbonate conten	A	5r	I
23. Biogenic silica	A	6	I
24. Stable isotopes (C, H, N, O, S)	A	6	I
25. Pollen and spores	A	3d,4d,5d	H
26. Diatoms	A	4d,5d	H
27. Macrofossils (plant and animal)	A	3d,4d,7	G
28. Ostracodes (including geochemistry and isotopes)	A	4d,5,7	G
29. Radiocarbon	Dt	2,3,7	I
30. 210Pb and 137Cs (and related isotopes)	Dt	4,5	F
31. Magnetic remanence (paleomagnetic) measurements	Dt	1	D-F
32. Varve counting	Dt	1	H
33. Tephra analysis	Dt	4, 5, 6	H-I
34. Other dating methods (e.g. Uranium series, TL/OSL/ESR)	Dt	4-8	F-I

5.5.3 Notes on Specific Sampling and Analytical Methods

The following material forms a general guideline for logging, sampling, and analytical methods for paleoclimatic reconstructions from cores of lacustrine sediments. These are only general comments, so that consultation of other sources is recommended. These sources include those listed in Appendix 1, as well as review papers and books about individual methods, as cited below. Some of the material, especially that on analytical methods, is adapted from the PALE protocols document (PALE Steering Committee, 1994). Note that analytical methods discussed here do not appear in the same order as they do in Table 1, which lists them in approximately the order in which they should be performed or their samples taken. The list here is rearranged slightly to group major classes of analyses (e.g. physical, chemical, biological) together.

Logging Methods

5.5.3.1 Magnetic Susceptibility

Magnetic susceptibility is a sediment property related to the concentration of magnetite and similar magnetic minerals
(Thompson and Oldfield, 1986; Reynolds and King, 1995; see magnetic properties section below). Whole core, pass-through, volume susceptibility at resolutions of 2-3 cm has become routine and should be measured in almost all cases. It can be conveniently measured at the drilling site with a portable coil and laptop computer. Coil calibration is extremely important. Several methods are available for finer-scale measurements after the core is split, including high-sensitivity devices that pass close to the split face of the core, and devices that measure susceptibility (and other magnetic properties) on very small samples. Although susceptibility is an indication of sediment provenance and style of deposition and provides a valuable core-to-core correlation tool (e.g. Andrews and Jennings 1987; Peck et al., 1994), detailed interpretation of the susceptibility signal requires considerable supporting data from other magnetic properties.

5.5.3.2 GRAPE

GRAPE (gamma-ray attenuation porosity estimator) provides an easy, continuous measure of porosity and bulk density (Boyce, 1976). However, both porosity values and p-wave velo-cities (next section) measured by logging tools need to be calibrated against measurements made by standard methods (e.g. Bulk Density section, below). Use of gamma-ray sources may require radiation safety certification.

5.5.3.3 P-wave (sound) Velocity, Resistivity, and other Logging

P-wave velocity provides another useful measure of bulk physical properties of sediment , which is primarily related to por-osity, particle density, and degree of cementation. P-wave velocity measurements are required to produce synthetic seismograms in seismic-reflection studies (e.g. Moore et al., 1995), which are useful for correlating core data with seismic-reflection data, allowing core-site-specific information to be spatially extrapolated.

5.5.3.4 Sensitive Geochemical Samples

Pore water and dissolved gas (e.g. methane) measurements, as well as some organic and sulfur geochemical analyses, need to be made on samples that have had minimum exposure to air. Pore water can be sampled through the core liner, and Eh-pH measurements can also be measured with instruments that pene-trate the liner. In some cases, this may be the only way to obtain accurate measurements and some of the measurements are best done at the drill site immediately upon recovery of the core. However, these devices may also disturb the sediments or allow oxygen to penetrate the core liner. Decisions about the relative importance of these type of measurements compared to their potential disturbance need to be made in advance.

Description Methods

5.5.3.5 Core Splitting

Cores should be split into two halves using materials and procedures that will minimize disturbance and contamination, especially that related to organic geochemistry and sediment magnetic properties. In general, one half of the core should be designated as the working half, and the other preserved as an archive half. In some cases, preservation of one-fourth of the core or discrete samples as archives may be acceptable. Use of the archive half for non-destructive analyses or for critical samples should be done at the discretion of the project leaders or sampling coordinator.

5.5.3.6 Photography

Basic photography of split cores sediments documents changes of sediment color and texture that are often important indi-cations of changes in the rates and processes of sedimentation in lakes. These changes also aid in correlation between cores from a single lake. The cores should be carefully split and the fresh exposed surfaces photographed with a high quality color film. Each photograph should include a standard color chart so that changes in color can be calibrated along a core. It is also important to photograph the cores soon after they are split, as the colors of the sediments can often change quickly. In addition to detailed photos, overview photos of several core sections are recommended to document large-scale changes.

5.5.3.7 X-ray Images

X-ray images (commonly contact prints at a scale of 1:1) of whole or split core are commonly useful for observing bedding, laminations, and other sedimentary structures, even when the core is visually homogeneous. X-radiography also helps to locate macrofossils (e.g., calcareous fossils and wood) for dating and analysis. X-rays images may not be necessary for obviously laminated cores for which continuous thin sections will be made. Care must be taken not to X-ray samples that might be used for dating methods based on electron traps in crystalline structures (dating methods section, below).

Image analysis of X-radiograph and (or) photographic images can overcome the discontinuous nature of sediment properties derived from samples taken at fixed and discrete intervals. Image analysis can show changes in sediment color, density, and structure at very high resolutions (several pixels/mm). Studies of these "continuous" changes can be carried out by means of an image analysis system using a video camera and appropriate computer software (e.g. Schaaf and Thurow, 1994).

5.5.3.8 Gray-scale Measurements and Multi-spectral Scanning

Various kinds of light-reflection scanning have proven useful for some marine cores (Barranco et al., 1989). Gray-scale profiles can be made from photographs of the core or thin sections. Hand-held sensors that attach to portable computers are also available. Equipment for full-spectrum light scanning is expensive and not commonly available. The importance of these methods for cores from continental environments has not been extensively investigated.

5.5.3.9 Thin Sections

Thin sections are valuable for a variety of lithological studies and are required for some, such as varve counting (see dating methods, below). Thin sections commonly reveal details of sediment structure, such as varves or fine laminations (e.g. Saarnisto, 1986). Most methods include freeze-drying and impregnation of the sediment with resin (e.g. Anderson and Dean, 1988).

5.5.3.10 Smear-slides

Observations made from smear slides are simple and powerful complement to lithological descriptions, and can be performed before most other sampling. Information from smear slides is commonly very useful, and should be made available as soon as possible. Smear-slide information can be used to guide subsequent sampling, making other analyses more efficient.

5.5.3.11 Visual Descriptions

A standard protocol should be adopted for core description, including lithological and sedimentological classifications and procedures. At a minimum, all classification terms must be defined. Munsell colors and Troels-Smith symbols (Troels-Smith, 1955) are recommended. Descriptions should be done by one worker (with sedimentological training) for the entire core in order to maintain consistency. ODP guidelines (Appendix 1) and Berglund (1986) are useful for such description and sedimentological protocols.

5.5.3.12 Bulk Sampling

Several considerations are important for bulk sampling of cores for analytical work. The condition of samples required for each analysis (Table 1) must be considered foremost. In general, core material is never sufficient for all analytical needs, so conservation of material and efficiency should be considered. For example, samples taken in plastic cubes for magnetic properties and remanence analyses are often suitable for a variety of other analyses once the magnetic measurements are made. Finally, samples for some analyses should be taken at the same depths in the core as those for other analyses in order to derive the maximum information from the combined analyses. For examples, samples for sediment grain-size and mineralogical analyses should be closely associated with samples taken for magnetic property measurements.

Analytical Methods

5.5.3.13 Sediment Magnetic Properties

Measurements designed to reveal changes in the concent-ration of magnetic minerals, their grain size, and their mineralogic composition (so-called rock- or mineral-magnetic properties) have become a much more frequent and informative aspect of lake sediment studies over the last 20 years. Increasingly, these measurements are being related to climate variables and used in paleoclimatic studies (e.g. Peck et al., 1994; Creer and Morris, 1996). In addition, magnetic properties often provide a strong basis for local to regional core-to-core correlations.

Magnetic property measurements have the advantages of being relatively cheap and simple to perform, largely non-destructive, and readily combined with paleomagnetic studies. Measurements can be carried out on either a constant volume or a mass specific basis. If paleomagnetic measurements are intended, stand-ard cubes should be used and all measurement carried out on a constant volume of fresh sediment. Paleomagnetic measurements can be carried out after low field susceptibility has been measured, but must precede all other rock magnetic measurements. Both rock- and paleomagnetic properties can degrade with long storage so it is best to carry out both as early as possible after subsampling.

Since the early work summarized in Thompson and Oldfield (1986), interpretative models of changes in magnetic properties in lake sediments have become increasingly complex (King and Channel, 1991; Reynolds and King, 1995). This has been in response to the realization that many factors other than simple sediment-source linkages can contribute to the properties measured under the broad heading of 'environmental magnetism'. These include particle sorting, dissolution diagenesis, authigenic sulphide formation, and biosynthesis of magnetite either as magnetosomes or as an extracellular product. In many cases, this rather complex range of environmental influences enriches the information to be gained from magnetic measurements, though it reinforces the need to avoid simplistic interpretations and to view the magnetic property record within the context of the full range of proxy measurements completed.

The range of magnetic measurements commonly carried out on sediment cores includes low field susceptibility, often at two frequencies, followed by a suite of remanence measurements that require equipment for magnetizing the sample as well as for measuring the remanence acquired. Qualitative and sometimes partially quantitative insights into the changing magnetic grain size and mineralogical components of a suite of samples can be gained in this way. An alternative or additional approach is to derive a series of parameters from direct magnetic hysteresis-loop measurements. Beyond these fairly standard properties are a range of often more time-consuming experiments designed to characterize more fully a smaller number of samples.

5.5.3.14 Bulk density, Water Content

Calculations of fluxes for any sediment constituent require measurements of sediment density. Samples should be carefully taken at appropriate intervals using standard volumes (e.g., syr-inges or paleomagnetic cubes). Wet volume density can be determined by simply weighing the sample container, subtracting the weight of the container, and dividing by the volume. Samples can then be slowly air dried (at up to about 60 °C) and re-weighed. This measurement allows the dry volume density to be calculated (g/cc) and, with comparison to the wet volume density, allows the weight percentage of water in the original sample to be calculated. An alternative method is to measure particle density. (e.g. by pycnometer) and to determine water content without using known volumes.

5.5.3.15 Granulometry

Sediment textures and grain-size distributions should be described in standard sedimentological terminology and size classes. Details of grain-size determinations are given in many texts (e.g., Lewis, 1984), and applications to lake sediments are discussed in Berglund (1986). In some cases, texture and grain size can be interpreted directly in terms of climatic variables, such as wind speed (e.g. Halfman and Johnson, 1984). The sand fraction is usually determined by shaking through a series of nested sieves. Material finer than 0.063 mm is commonly determined by use of a Sedigraph or by automatic particle counters based on light or resistivity. It can also be determined by pipette methods (e.g. Syvitski, 1991), which has the advantage of retaining size fractions for further analysis.

5.5.3.16 Elemental Chemical Analysis

Elemental composition has been used to identify distinct layers such as volcanic ash. In addition, variations in elemental composition of autochthonous and allochthonous sediment fractions have been used to document soil erosion and development, vegetation change, and limnological conditions (e.g., Mackereth 1966; Engstrom and Wright, 1984; MacDonald et al. 1993). Such changes may be a direct result of climatic changes and (or) in-direct results of changes in watershed conditions. Major-element geochemistry, especially that related to authigenic minerals, may reveal a variety of important information about the evolution of chemical processes in a lake (e.g. Kelts and Talbot, 1990; Dean, 1993).

Studies of trace metals in lake sediments mostly have focused on understanding of anthropogenic contaminants (e.g. Lottermoser et al., 1993; Renberg et al., 1994). Potential paleoclimatic signatures related to trace metals have not been established, although trace metals are of chronostratigraphic value because the timing of global dispersal of certain anthropogenic pollutants is well-documented in ice cores and lake sediments (e.g. Hong et al., 1994; Lottermoser et al., 1993)

Geochemical methods are diverse; good starting points for lake sediments include Engstrom and Wright (1984); Bengtsson and Enell (1986). Recommended analytical procedures range widely, depending greatly on the availability of hardware. Useful studies can be carried out using simple titration and petrographic microscopic analyses. Well-equipped laboratories would bring modern analytical approaches, ranging from atomic absorption (AA) spectrophotometry, neutron activation analysis (NAA), inductively-coupled plasma mass spectrometry (ICP-MS), X-ray fluor-escence (XRF), scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS), and others to bear on the problem of sediment composition.

5.5.3.17 X-ray Mineralogy

Mineralogy of the clay and fine silt size fraction is useful in many paleoenvironmental studies. For example, it can be used to distinguish between sediments derived from within the basin versus those imported from extra-regional sources by wind. At somewhat lower resolution, the suite of clay minerals transported to lake basins from their watershed are responsive both to climatic variables such as temperature and precipitation, and to climatically mediated watershed processes such as soil erosion (Jones and Bowser, 1978). Mineralogy of the carbonate fractions is an important complement to information derived from carbonate-content and major-element analyses (Kelts and Talbot, 1990; Dean, 1993).

Analyses are most commonly carried out by X-ray diffract-ion methods (Lewis, 1984). Details of the quantification of X-ray diffraction curves for lake and marine sediments vary (Andrews et al., 1989; McManus 1991).

5.5.3.18 Sand/Silt Mineralogy

The use of the mineralogy of the sand and coarse silt fract-ion is similar to that for clay minerals, except that the course fract-ion may reveal information about processes that are sensitive to particle size and depositional energy, such as eolian deposition or shallow-water transport (lake-level information). Methods are simil-ar to those for clay mineralogy, except that the coarse fraction is usually ground to smaller grain size before mineralogic analysis.

5.5.3.19 Organic Carbon and Nitrogen (± LOI)

The amount of organic carbon and nitrogen in lake sediments is a fundamental property that is a function of autochthonous and allochthonous organic production, bacterial decay, and the rate of clastic sediment input. As measures of lake productivity, organic carbon and nitrogen are critical for paleoecological studies. The ratio of carbon to nitrogen is commonly an indication of the source of the organic matter (Stein, 1991).

Although the determination of the organic carbon content of the sediment is an important parameter to measure, there is no single standard method that has been applied to this measurement. Loss of weight on ignition (LOI) (Bengtsson and Enell, 1986) is the simplest method, although constituents other than carbon may contribute to weight loss. Wet-chemical methods are also used for both carbon and nitrogen (Hedges and Stern, 1984); carbon contents from LOI and wet-chemical approaches have a significant correlation when paired samples are analyzed. Organic carbon and nitrogen can also be determined by automated carbon analyzer (e.g. Weliky, et al. 1983) and by carbon-hydrogen-nitrogen (CHN) analyzer (e.g. Hedges and Stern, 1984). See Organic Geochemistry section for more information.

5.5.3.20 Organic Geochemistry

Organic matter (OM) that is preserved in lake sediments encompasses a range of compounds, from the simple such as methane, to complex biopolymeric molecules such as lignins and nucleic acids. In a lacustrine environment, OM is derived from primary production within the water column and also from terrest-rial biota by transport of leached and eroded material into the lake. The accumulation and composition of OM in the sediments is usually influenced by the environmental conditions: climate, geology of surrounding rocks, physical and chemical characteristics of the lake waters, and the nature of the OM itself (Meyers and Ishiwatari, 1993; Killops and Killops, 1993). Hence, variations in source materials and conditions can effect the composition of the organic compounds in sediments, and these can potentially be used as a chemical record of past change.

Many of the organic chemical constituents of fresh OM are labile, and may be transformed or completely remineralized within the water column and in surficial sediments. In a similar way to conventional fossil record, therefore, only resistant molecules tend to survive, and these are most commonly used to deconvolve the history of changing inputs to the lake sediments. Biological markers (or chemical fossils) are particularly useful compounds in this respect. They have a direct chemical link with a biologically occurring precursor. Certain lipids and pigments have a restricted occurrence in only a few organisms or types of organisms; if they or their derivatives can be identified, then an attempt to discern original inputs to the sediments can be made. For example, biological markers can clearly discern autochthonous and allochthonous contributions to lake sediments (Meyers and Ishiwatari, 1993), and have the potential to be used in quantitat-ive assessments of changing OM inputs (e.g. Prahl et al., 1994). These biological markers include fossil pigments (chlorophylls and their derivatives, especially carotenoids; Sanger, 1988; Leavitt, 1993) and lignin oxidation products (e.g. Orem et al., 1996). Fossil pigments are also useful for reconstructing the history of productivity, meromixes, and trophic status (Brown et al., 1984; Züllig, 1989; Guilizzoni and Lami, 1992).

The fixation of carbon by photosynthesis, by both land and aquatic plants leads to isotopic fractionation in favor of the lighter isotope of carbon 12C (more information in Stable Isotope section). This fractionation of approximately 20 parts per 1000 (20) relative to CO2 has important consequences. Again, changing environmental conditions can lead to the changing isotopic signature of OM; this can lead to isotopic shifts in the composition of sedimentary OM, for example as a result of increasing aquatic productivity (Schelske and Hodell, 1995). More interestingly, a combination of the molecular and isotopic approach can allow distinction of OM at the species level. Although this aspect of organic geochemistry is in its infancy, the potential is tremendous (Rieley et al., 1991).

The determination of molecular parameters is a rather time consuming process. Careful handling is necessary to avoid contamination and some materials need extra care (i.e. kept froz-en). Analytical methods require the separation of individual compounds by chromatography (gas chromatography, high performance liquid chromatography) and their identification, usually by mass spectrometry. Fortunately, there is a huge wealth of literature on the identification of biological markers (for reviews see Peters and Moldowan; 1993) and Engel and Macko; 1993)).

5.5.3.21 Sulfur Geochemistry

The amount, kind, and isotopic composition of sulfur species in lake sediments can potentially reveal much information about productivity, sulfate availability, surface runoff, and post-depositional alteration (Berner, 1984, Tuttle et al., 1990; Bates et al., 1993, 1995; Vairavamurthy and Schoonen, 1994). Sulfur exists in a variety of oxidation states and its geochemistry is linked with that of carbon. In addition, sulfur diagenesis affects magnetic mineralogy. Although sulfur geochemistry is complex, it has been successfully applied to studies of ancient and modern lakes to help understand depositional and diagenetic processes related to changes in climate, productivity, and water chemistry. Sulfur geochemical methods, however, have not been widely used for paleoclimate studies, and their potential has not been fully tapped. For this reason, it is relatively undeveloped as a paleoenvironmental proxy, despite its great potential. Nevertheless, large systematic changes in the abundance and isotopic composition of pyritic sulfur are generally the result of variations in the supply of sulfate to a lake from rainfall runoff. A shift to warmer, wetter conditions, such as that experienced by some areas during the early Holocene, may be marked by an increase in the abundance of pyritic sulfur and a negative shift in sulfur isotope composition (Spiker and Bates, 1993).

Sulfur species commonly analyzed include disulfide "pyrite" sulfur (S2-), "acid-volatile" sulfur (S- in monosulfide minerals, e.g. greigite and pyhhrotite), organic sulfur (S in kerogen and bitumen), and sulfate sulfur (Tuttle et al., 1986, Bates et al., 1993). Sulfur isotopes (34S/32S ratios) are generally measured on the pyrite and organic-sulfur fractions, although they can be measured in all major fractions depending on abundance. Analytical methods are discussed in Bates et al. (1993).

5.5.3.22 Carbonate content

The carbonate content of lake sediments, composed of detrital, authigenic, and biogenic components, reflects the chemical limnology of the basin as well as biological activity (Kelts and Hsü, 1978; Talbot, 1990; Eugster and Kelts, 1983). The relative amounts of detrital and authigenic carbonate are particularly sens-itive to drainage basin conditions of many lakes; both transport of detrital sediment to the lake and chemical precipitation of carbonates respond in different ways to climatic changes. The chemistry and mineralogy of authigenic carbonate phases are also sensitive to climatic and drainage basin conditions (e.g. Dean, 1973). Authigenic and biogenic carbonates are the primary materials for many isotopic studies (Stable Isotopes section).

Total carbonate is usually measured by volumetric methods on CO2 evolved during reaction with acids, or by difference between total carbon and organic carbon measured by other means (Organic Carbon section). Carbonate mineralogy and chemistry are ordinarily determined by X-ray diffraction (X-ray

Mineralogy section) and elemental methods (Elemental Chemistry section), respectively.

5.5.3.23 Biogenic Silica

Biogenic silica, produced mostly by diatoms, is a major component of lake sediments in many environments. Other components that contribute to biogenic silica include phytoliths, chrysophyte cysts, and sponge spicules. Down-core variations in biogenic silica reflect primarily changes in diatom productivity (e.g. Colman et al., 1995), which is a complex response to a variety of physical and chemical properties of the water column, as well as such variables as nutrient and light availability. Water chemistry and sedimentation rates also affects the amount of biogenic silica that escapes dissolution to be preserved in the sediments.

Biogenic silica is equated with opaline silica, which can be measured by wet-chemical methods. A variety of methods are in use (Battarbee, 1986; DeMaster, 1981; Mortlock and Froelich, 1989). In some methods, a correction can be made for the silica contributed by fine-grained clays that inevitably dissolve along with the opaline silica (Mortlock and Froelich, 1989; Colman et al., 1995).

5.5.3.24 Stable Isotopes (C, H, N, O, S)

A wide variety of chemical and biological processes cause fractionation of stable isotopes in lake sediments, so that analysis of the isotopic composition of various components of the sediment allows inferences about the history of climatic and other environmental conditions in the lake. Oxygen and carbon isotopes in carbonates precipitated from the water column, either organically or inorganically, have been most commonly analyzed (e.g. Lister, 1988; 1989; Schwalb et al., 1994). Oxygen and carbon isotopes in temperate lakes reflect the isotopic composition of met-eoric water, the composition and source of which has important paleoclimatic implications (Stuiver, 1970). These isotopic compositions are subsequently modified by limnological (e.g. evaporation) and biological processes (Talbot, 1990). Studies that monit-or and model modern isotopic composition of lake and meteoric water (e.g. Hostetler and Benson, 1994) are important for reconstructing these processes. Although carbonates are the most common and straight forward materials for isotopic studies, siliceous materials (such as diatoms, chrysophyte cysts, and sponge spicules) have some potential.

Carbon isotopes of organic matter are another important paleolimnological tool, since photosynthesis causes significant fract-ionation of carbon isotopes (Organic Geochemistry section). Although the processes are complex. carbon isotopes in organic matter are important reflections of productivity, aquatic vegetation type, and other biological factors (McKenzie, 1985). Also promising are isotopic measurements on specific organic matter components (e.g. hydrogen isotopes in lignin; Krishnamurthy et al., 1995).

Valuable paleolimnological and paleoclimatic information is also potentially available from nitrogen and sulfur (Sulfur Geochemistry section) isotopes. However, these methods still need much additional basic research.

A variety of methods are used to separate materials for isotopic analyses. The actual isotopic measurements are usually made by standard mass spectrometer methods. The references cited above and Fritz and Fontes (1980) are useful sources of additional information on methods.

5.5.3.25 Pollen and Spores

Pollen and spores in lake sediments have always been a mainstay of continental paleoclimatic reconstructions. Pollen and spores provide information about changes in the composition and spatial patterning of late Quaternary vegetation that can be used to infer regional paleoclimatic changes. Pollen analyses provide information on changes occurring both on land and in the water body itself. Pollen spectra also show how different vegetation types, whose response times can vary dramatically, react to climate change. Pollen can also be combined with plant microfossils to reconstruct lake-level changes (e.g. Schneider and Tobolski, 1985).

Different types of lakes preserve different vegetation signals, ranging from aquatic vegetation in the lake itself, to vegetat-ion in the drainage basin, to composites of regional vegetation. In small lakes or in shallow sections of large lakes, plant macrofossils and pollen grains and spores of aquatic vegetation are more abundant. However, the risk of hiatuses is higher in these environments. In deeper and larger lakes, pollen is more likely to provide information about regional upland vegetation. Large deep lakes typically have higher sedimentation rates and fewer hiatuses. Ideal-ly, both shallow and deep lakes in the same area should be cored for their complementary information. In varved lakes, pollen analys-es can yield annual to seasonal resolution of reconstructed vegetat-ion (e.g. Peglar, 1993). High-resolution studies in which pollen is combined with other paleoecological indicators are especially useful for documenting rapid changes (e.g. Van Geel et al., 1989), including human disturbance of natural vegetation.

Theoretically, pollen in lake sediments can be used to reconstruct precise vegetation assemblages, and vegetation can be used to directly reconstruct climate variables (e.g. Elk Lake: Whitlock et al., 1993; Bartlein and Whitlock, 1993). These linkages lead to close relationships between vegetational and climatic modeling (e.g. Harrison et al., 1995). Statistical methods for these reconstructions include closest-analog methods (Overpeck, 1989) and transfer functions (e.g. Guiot, 1987). Two major problems, lack of modern analogs for past pollen spectra and human disturbance of modern vegetation, introduce uncertainty into these reconstructions, so they should be used with caution. In any case, modern samples from comparable depositional settings need to be collected for the study region, in order to provide the best calibrations possible for the relationships of pollen to vegetation and veget-ation to climate. In large lakes, a network of surface-sediment samples in different depositional environments is needed.

Major regional reconstructions of paleovegetation from pollen studies include Bartlein et al., 1986; COHMAP members, 1988; Webb et al., 1993; and Guiot et al., 1993). Pollen spect-ra of long sections can be compared to the marine oxygen-isotope record, either directly in the same (marine) cores (e.g. Dupont, 1993), or indirectly, through spectral and correlation statistical techniques (e.g. Hooghiemstra et al., 1993).

Pollen and spores must be extracted from the sediments and analyzed in a consistent manner to ensure comparability of results among laboratories. Recommended guides to laboratory procedures, especially physical and chemical extraction of microfossils, include Faegri and Iversen (1989) and Moore et al. (1991). Exotic markers should be added to all samples, so that pollen concentrations can be calculated in addition to percentages. Where time control is sufficient, pollen fluxes can be calculated from concentrations.

5.5.3.26 Diatoms and other Siliceous Microfossils

Diatoms and other limnic microfossils are especially important because their abundance and distribution is controlled directly by physical and chemical limnology. Direct reconstruction of paleolimnological variables is possible (e.g. Bradbury, 1988; Bradbury and Dieterich-Rurup, 1993; Gasse and Fontes, 1989), although taxonomic uncertainties and incomplete understanding of environmental factors that control species distributions limit paleoenvironmental interpretations. Nevertheless, diatoms are the primary source of paleolimnological information for many lakes.

For diatoms, general separation and counting methods are fairly well established (Battarbee, 1986). Surficial lake sediments should be collected near the center of the basin and in other depositional environments (e.g., littoral or euphotic zone, fluvial communities) for modern ecological calibration. Measurements of water conductivity, pH, surface temperature, and secche disk depth should be made in the field. In addition, water samples must be collected for the calibration of water chemistry with modern and fossil assemblages.

For other siliceous microfossils (such as sponge spicules, phytoliths, and chrysophyte stomatocysts and scales), the diatom processing procedure is suitable in most cases. These microfossils will be observed in the course of diatom enumeration, and notes should be taken to determine if further exploration is warranted.

5.5.3.27 Macrofossils (Plant and Animal)

Studies of macrofossils, "any part (of an organism) preserved after death which does not require a high-power microscope to see it, and which can be manipulated by hand (Birks, 1980)," in lakes contribute most to paleoecological reconstructions when used in combination with pollen analysis. Macrofossils include seeds, leaves, wood, conifer needles, fish bones, mollusks, insects, and other remains. The advantage of macrofossils is that they may be identified to species level much more easily and frequently than pollen. Thus they can provide critical taxonomic clarification. Macrofossil presence in sediments indicates local presence on the paleolandscape (Birks 1980; Glaser 1981), which allows spatial refinement of paleo-distributions not usually possible with pollen. Macrofossil distribution and abundance in lakes varies considerably, depending on specific characteristics of the lake and vegetation. In general, however, lakes selected as regional pollen sites will not be the most suitable sites for macrofossil studies: a compromise usually arises in which multiple cores are taken and macro-fossils retrieved from lake-margin cores, which must be correlated to central pollen cores. Guidelines for methods and interpretation of macrofossils include Berglund (1986); Birks (1980); and Wasylikowa (1986).

5.5.3.28 Ostracodes (including Geochemistry and Isotopes)

Continental ostracodes are small bivalved crustaceans that live in many permanent and ephemeral aquatic environments. The physical and chemical properties of the environment determine which species may live there; environmental tolerances vary widely with species. Ostracode valves, which are made of calcite, are common fossils. Ostracode species assemblages as well as the isotope values and trace-metal ratios of their valves provide a wide variety of paleolimnological information (DeDeckker and Forester, 1988). For many species, the modern distribution and related environmental variables have been documented (e.g. Delorme, 1989). From such information, hydrochemistry and temperature response surfaces have been constructed for various species assemblages (Forester, 1991; Smith, 1993).

Trace metal ratios (Mg/Ca, Sr/Ca) from ostracode valves are related to water temperature, salinity, and perhaps other fact-ors during calcification (DeDeckker, 1988; Engstrom and Nelson, 1991; Holmes, 1996). Ostracodes also are a source of biogenic calcite that is at or near isotopic equilibrium with lake water, for stable isotope analyses (e.g. Forester et al., 1994; Schwalb et al., 1994; Heaton et al., 1995; see also stable isotope section). They are also useful material for AMS radiocarbon analyses (Colman et al., 1990).

Continental ostracodes are small and their valves are oft-en fragile. The sand-size valves must be separated from the bulk sediment with care, using techniques such as freezing the sediment to aid dispersion, followed by gentle washing and sieving, and hand picking.

Dating Methods

5.5.3.29 Radiocarbon

Radiocarbon analyses are, of course, the mainstay of chronology for lake sediments less than about 40,000 years old. Many books have been written about sampling and analytical methods for radiocarbon dating as well as interpretation of the results. An entire journal (Radiocarbon) is devoted to the subject. Accelerator-Mass Spectrometer (AMS) methods have allowed small samples of individual components of lakes sediments, such as macrofossils, to be analyzed separately (e.g. Hajdas et al., 1995). An important issue related to lake sediments is the calibration of the radiocarbon time scale with the sidereal (calendar) one (Stuiver et al., 1991).

Three problems are especially prevalent in analyses of lake sediments:
- reservoir effects, in which dissolved CO2 in the lake is not in equilibrium with the atmosphere (e.g. the "hard-water effect" produced by groundwater containing CO2 dissolved from bedrock);
- the contribution to lakes of detrital carbon, which is older than the sediments in which it is deposited;
- recycling, resuspension, and redeposition of previously deposited material.

The carbon fraction that yields the most accurate age depends on the lake system studied. In some cases, biogenic carbonate may give the best results if reservoir effects can be evaluated by dating shell collected live before atmospheric nuclear testing (e.g. Rea and Colman, 1995). Where detrital organic carbon input is high, the humic acid fraction may concentrate less refractory, autochthonous organic carbon; in other cases, particularly old samples not kept frozen, humic acids may concentrate modern microbial contamination. Pollen extracts may also yield accurate results (Brown et al., 1989). In general, analyses of total organic carbon (TOC) are difficult to evaluate, although, where other data show that most of the carbon is autochthonous (e.g. Colman et al., 1996), such ages may be acceptable.

5.5.3.30 210Pb and 137Cs (and related Isotopes)

Lead-210 profiles offer one of the best ways of obtaining high-resolution chronologies for the recent past (100-150 years). However, chronologies and dry-mass sedimentation rates derived from 210Pb measurements may be highly model-dependent (Appleby and Oldfield, 1992). This is especially true where sedimentation regimes have changed through time. Measurements of dry mass and wet volume coupled with the use of additional dating constraints and (or) multiple profiles often allow the assumptions underlying the alternative models to be tested.

Measurements of 210Pb are made either by direct gamma assay (Appleby et al., 1988) or through the decay of its alpha-emitting grand-daughter 210Po (Robbins, 1978). The advantages of the former approach are that the procedures are non-destruct-ive and simultaneous measurements of 137Cs, 134Cs and, in a sufficiently low-background detector, 241Am (Appleby and Oldfield, 1992) can be made. Moreover, estimates of changing 226Ra-supported 210Pb levels can be obtained by measuring the activity of the short-lived parent 214Pb, provided procedures are adopted either to preclude or to allow for the effects of radon escape. Direct gamma measurements are thus very useful where samples are required for subsequent analysis, where the additional constraints on age-depth calculation provided by fall-out radioisotope profiles are needed, or where changes in sediment type and source make variations in the level of 226Ra-supported activity likely. The sample mass required varies with the type of detector used, but may be less than a gram in relatively high-activity samples.

The advantages of the second approach, using alpha spectroscopy, include speed and economy. In most cases, 226Ra-supported activity is estimated from the 'tail' of the 210Pb versus depth curve and assumed to be relatively constant. Alternatively, separate measurements of 226Ra activity can be made.

5.5.3.31 Magnetic Remanence (Paleomagnetic) measurements

Depositional remanent magnetism (DRM), one form of natural remanent magnetism (NRM), is a critical chronological component of lake sediment studies, to the degree to which those sediments faithfully record the earth's magnetic field at the time of deposition. Magnetic reversal stratigraphy is somewhat peripheral, because the youngest magnetic reversal, the Brunhes-Matuyama (ca. 780 ka; Baksi et al., 1992), is beyond the time period emphasized here. However, the Brunhes-Matuyama boundary commonly is useful for constraining younger age estimates based on sedimentation rates or on the number of 100,000-yr climate cycles.

Within the Brunhes chron, about a dozen so-called excursions have been identified and dated (e.g. Champion et al., 1988). These large-scale transient changes in apparent field position are potentially valuable chronostratigraphic markers. Nothing uniquely identifies a given excursion, however, and not all of them appear to be recorded globally. Apparent excursions can be caused by core disturbance, so great care must be used in identifying them.

Changes in the non-dipole component of the earth's magnetic field lead to small-amplitude, regional magnetic-field changes (secular variation). Secular variation curves for different regions dated by radiocarbon or varve-counting methods can be used for time control by correlation (e.g. Lund, 1993), but, as for excursions, additional time constraint is required for unique matching of curves. Core disturbance and post-depositional alteration must also be eliminated.

Finally, changes in the relative intensity (measured intensity normalized to another magnetic property) of the earth's magnetic field have the potential to provide correlations to dated sequences (e.g. Peck et al., 1996). Special care must be taken to test whether the sediments are suitable for recording relative intensity (King et al., 1983) and that variations in relative intensity are not caused by one of many depositional and post-depositional processes, rather than the field intensity at the time of deposition.

Samples for paleomagnetic analyses (Collinson, 1983) are generally taken in small plastic boxes pushed carefully into the split face of the core. Samples need to be "cleaned" to appropriate levels determined from step-wise alternating field and (or) thermal demagnetization. A variety of other tests are needed to ensure that the measured remanance is primarily depositional.

5.5.3.32 Varve Counting

Varved lake sediments are extremely valuable in limnological and paleoclimatic studies because of their annual, and in some circumstances, seasonal, time resolution (Anderson and Dean, 1988). In most cases, the annual nature of the laminations needs to be demonstrated using independent time control, and even then, varves may occasionally be missing. Varve formation can also be documented by sediment-trap studies (e.g. Thunell et al., 1993).

Varve thickness itself is an important indication of limnological and watershed processes, and when the annual nature of the varves is combined with other climatic and limnological proxies, extremely valuable inferences can be drawn (e.g. Lotter, 1991; Anderson, 1993; Goslar et al., 1995; Zolitschka and Negendank, 1996).

Varve thickness is the most common parameter measured in paleolimnological studies, but other variables can be measured as well. Varves are usually measured and counted in thin section (see Thin Sections, above). Changes in thickness of varves or laminae can be determined by adapting methods derived from dendrochronology (Thetford et al., 1991). X-radiography of uniform-thickness core slabs also provides useful images for varve and lamination analysis.

5.5.3.33 Tephra Analysis

Volcanic tephra, in addition to its direct and indirect affects on climate and vegetation, is an important part of the chrono-logy of lake sediments in many areas. This is because tephra layers form essentially isochronous horizons that are relatively easy to correlated on the basis of chemistry and mineraology, from independently dated sites to other sites. Recent research into tephra distribution has shown that the geographical extent of volcanic ash distribution previously has been consistently and seriously underestimated. Extensive studies in European peats and lake sediments show that these deposits contain microscopic layers of fine Icelandic volcanic ash (e.g. Pilcher and Hall, 1996). Advanced analytical techniques, especially for single shards, allows geochemically confirmed site linkage over extensive areas, which, combined with high-precision multi-sample 14C ages of sediments containing tephra, has resulted in chronologies that, under optimum conditions, are comparable to the dendrochronological time scale.

Tephra studies are especially useful when combined with regional stratigraphy and geological records to form a chronological framework for large areas (e.g. Sarna-Wojcicki and Davis, 1991). Chemical and mineralogical methods for identification and correlation of tephras are diverse (e.g. Westgate and Gorton,

1981) but relatively standard except for the application to small samples or single shards. Because tephras are preserved in many types of paleoclimate records (ice cores, tree rings, marine sediments) in addition to lake sediments, their usefulness in lacustrine paleoclimate studies is unlimited. PAGES currently has a major project involving explosive volcanism (PAGES Workshop report, Series 96-3: Climatic Impact of Explosive Volcanism; 1996).

5.5.3.34 Other Dating Methods

A variety of experimental or developing dating methods are applicable to lacustrine sediments. Uranium-series methods have provided reliable ages for several kinds of authigenic minerals (e.g. Bischoff et al., 1985; Lao and Benson, 1988). Experimental schemes based on Uranium-series isotopes in bulk sediment (e.g. Edgington et al., 1996) also have shown promise.

Various luminescence measurements-thermal (TL), optic-ally stimulated (OSL), and infra-red stimulated (IRSL)-also have potential for use with lake sediments (e.g. Berger, 1988; Godfrey-Smith et al., 1988). However, because of uncertainties about initi-al doses and degree of bleaching at the time of deposition of lake sediments, these methods have more commonly been used with other sediments such as loess and eolian sand. Electron-spin resonance (ESR) methods (Grün, 1989) have been used for chemically precipitated lake sediments, but still entail large uncertainties. Care must be taken to avoid exposure of samples for luminescence dating to light or X-rays.

These and other methods are particularly important for time control beyond the range of radiocarbon dating.

5.5.4 Other General Logging, Sampling, and Analysis Notes

· Whole-core, multi-sensor, logging instruments are available that measure magnetic susceptibility, GRAPE, and P-wave velocity in a single, automated pass-through of the core.
· Description, photography, scanning, and sampling should be performed as soon as possible after the cores are split.
· Samples for many methods that are of secondary importance and that would disturb the cores can be taken from material in the core catcher or from the very top and bottom ends of the core sections.
· The natural breaks in activities come: (1) after the cores have been logged, but before they are split, and (2) after time-critical description, measurement, and sampling activities.

5.5.5 Sample and Archive Material Availability

Information on the condition, storage, and availability of sample and (or) archive material is important (see Data Archive, below). Exclusive access to core and sample material by active project participants should be limited to a specific period of time, commonly two years. Unused core material should be made available to the general research community after this period.

5.6 Data Management and Dissemination

Data management is of vital importance for developing a global paleoclimate history from continental settings. Developing the continental record requires the synthesis of paleoclimate reconstructions from a mosaic of sites. In order to achieve this goal, both primary and secondary data from terrestrial sites must be archived in coherent file formats and made accessible to the research community. For this reason, it is a primary responsibility of any scientific investigator to contribute data to the PAGES Data Center, the World Data Center-A for Paleoclimatology in Boulder, Colorado, USA.

5.6.1 Data Coordination

Effective data coordination is essential for maximizing the success of any project. A data coordination program implemented at the point of project inception can expedite data processing and synthesis thereby making the data and results available to the general research community as soon as possible. Good data coordination is important for developing syntheses of project data in local, regional, and global contexts.

Facilitating data flow among project members is particul-arly important for large projects. An internal project database or data server may be necessary to provide access to all data associ-ated with the project. Access to the server could be through the internet, by mail using diskettes, and (or) through non electronic methods. The project data coordinator should be responsible for maintenance of the project database including:
· Development of effective and complete means of archiving group data and disseminating those data among group scientists;
· Construction and maintenance of a complete core depth scale, including drilling depths, drive depths, and core section depths;
· Keeping a sample inventory (depth, sample number, interval, thickness, amount of sediment, proxy(ies), investigator;
· Core archive material inventory, which is part of core storage and is needed to keep track of who gets archive material and information;
· Obtain and facilitate access to data necessary to complete the research outlined by the science questions for the overall project (e.g. historical meteorological data, solar forcing time series);
· Maintenance of the data for calibration and modern system characterization.

Recommendations for Data Coordination are already discussed at length in the PALE Research Protocols (PALE Steering Committee, 1994), and those recommendations should be consulted when building a data coordination program. However, some aspects of effective data coordination are important enough to be repeated here.

Data Coordinator
Every project should have a data coordinator. This person may be one of the principal investigators on the project. If the project is large, it might be appropriate for a non-researcher to be appointed data coordinator. The data coordinator should be responsible for maintaining a working database for the project, and making that database available to all members of the research group. The coordinator might also obtain other datasets of use to the project, or provide information on how to obtain useful data. Finally, the data coordinat-or should be responsible for collecting and formatting data for easy submission to the PAGES/WDC-A for Paleoclimatology database.

Data Synthesis
It is important to interpret proxy records obtained from a single site or group of sites in a global and regional context, and to assess the impacts of climate changes indicated by these proxies on ecosystems. These syntheses should be made with the idea that the data produced from the analyses and interpretations can be used for larger scale syntheses. Of particular importance is the usefulness of the data for GCM simulations and sensitivity experiments. For many projects, it may also be important to write summary papers in common language to be read by the general public.

Data Availability
Data should be put into the public domain as soon as possible, and no later than two years after the data set is complete, or immediately after its publication. Rapid availability of data is a responsibility of publicly funded research, and it is important to modern quantitative research activities related to global change science, among other things.

5.6.2 PAGES Data Archive

A primary responsibility of an investigator is to contribute data to the World Data Center-A for Paleoclimatology in Boulder, Colorado, USA. Data should be submitted to the data center in a timely manner, and a plan for submitting data should be made at the beginning of the project. Data should be submitted to the data center immediately after publication, and(or) two years after sample collection, whichever comes first.

Data submitted to the archive should be prepared in a logical file format that is consistent with the guidelines for submission of data to the World Data Center-A for Paleoclimatology. Data files may be ASCII, Spreadsheet, or other common computer formats. Data files can be sent by E-mail, FTP transfer, or via the postal system on diskettes or other media. Please direct inquires to: Mr. Bruce Bauer, data manager, bab@mail.ngdc.noaa.gov.

Submitted files should include the following information:
· Point or Time Series Data:data set name, latitude, longitude, bathymetry/elevation, contribut-ors, references, variable names, variable unit, data precision, data format, contact information (mail, phone, electronic mail).
· Mapped or Gridded Data Sets:data set name, latitudes of grid points, longitudes of grid points, time period represented by data, contributors, references, variable names, variable unit, data precision, data format, contact informat-ion (mail, phone, electronic mail).
· Optional Information: additional site information, brief description of data, methods including references, chronostratigraphic information, date of data generation.

Contributors are urged to examine existing WDC-A data sets for examples of important archival information. These data can be viewed via anonymous FTP (ftp.ngdc.noaa.gov; look in the paleo directory) or on the WDC-A's home page on the World Wide Web (http://www.ncdc.noaa.gov/paleo/paleo.html).

Addresses for World Data Center-A for Paleoclimatology:
E-mail: paleo@mail.ngdc.noaa.gov; FTP: ftp.ngdc.noaa.gov.

Files can be placed in the /pub directory.
Postal, WDC-A for Paleoclimatology, 325 Broadway, code E/GC, Boulder, CO 80303, USA

5.7 Publication Protocols

Research results for any project must be published in a timely manner. To ensure timely publication of results and interpreta-tions, and to avoid conflicts, a publication procedure and schedule should be developed at the beginning of the project. The nat-ure of such a schedule will vary according to the goals and size of each project, but some plan for the publication of results should be agreed upon in advance.

One procedure that has worked well in a variety of circumstances is publication of a comprehensive "Preliminary Results" report, authored by the generic team project members, which, in addition to the first set of results, contains an overview of the project, its organization, and its members. Project members generally agree to cite this initial publication in all subsequent topical and synthesis reports.

Publication of topical investigations should be completed in a timely manner so that syntheses of the proxy data in a regional and global context can be made. Syntheses and summaries need to be carefully balanced among topical studies and principle investigators; project Workshops or Symposia facilitate this proced-ure. Summary papers for the general public commonly prove helpful to the project as a whole, especially if they are focused on the impacts of climate change on landscapes and ecosystems.

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0. TABLE OF CONTENTS **6. TASK FORCES**

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5. RECOMMENDATIONS

6. LAKE DRILLING TASK FORCE

Obtaining long continental records requires a major investment in planning, logistics, and drilling technology in order to maximize chances of successfully recovering long, high quality records. It is important to select the most promising sites, conduct pre-drilling site evaluations, and select the most suitable drilling technology to carry out a successful program. To help facilitate a unified selection of sites, participants at the PAGES Workshop agreed to form a Task Force to organize a unified Global Change initiative for the International Continental Drilling Program (ICDP). Such an initiative would be a partnership between ICDP, which would support drilling operations and technology, and national or international science funding agencies, which would provide support for scientists and analytical work.

The Task Force solicited from the continental paleoclimate community two-page proposals for lakes that should be considered and prioritized for drilling support by ICDP. The proposals included a brief description of the lake(s) of choice; the rationale for selection in terms of scientific questions to be addressed, prospects for success, and logistical challenges to be anticipated; a list of participating scientists, and an estimated budget. More than 60 of these mini-proposals were submitted to the Task Force and were reviewed in October, 1995. More complete proposals were requested for the lake sites evaluated as having the highest priority by the Task Force. These materials were compiled into a five-year drilling plan, which was presented at the VIII International Contin-ental Drilling Symposium in February, 1996, in Tsukuba, Japan. The plan was also circulated to the international community for additional input. The plan was submitted to ICDP in April, 1996, as a "Prospectus for a Global Lake Drilling Initiative."

Individuals serving on the Task Force are the leaders of PEP I (V. Markgraf), PEP II (J. Dodson and Liu Tungsheng), PEP III (F. Gasse), the Baikal Drilling Project (D. Williams), the European Drilling Program (J. Negendank and S. Leroy), IDEAL (T. Johnson), and a representative from PAGES (S. Colman).

D. Williams served as head of the Task Force through submission of the "Prospectus"; S. Colman now serves in this capacity.

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6. LAKE DRILLING TASK FORCE

7. LINKAGES

Because continental drilling for paleoclimate records is intimately linked with the PEP transects, it has connections to a wide variety of other PAGES, IGBP, and external activities. The PEP transects, together with IMAGES and polar ice core projects, form the primary observational activities of PAGES. These observational activities are scientifically and philosophically linked to other efforts, especially climate modeling work and studies of the human dimensions of global change. The PANASH report (PAGES, 1995) offers a more detailed discussion of linkages to other global change research activities.

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8. SUMMARY

7. LINKAGES

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8. SUMMARY

The scientific importance of paleoclimate records derived from lacustrine sediments is difficult to over-emphasize. Continental records are needed to fully develop a global grid of sites that is necessary to document regional patterns of climate change, define regional- to local-scale responses to those climate changes, and to test climatic models at relevant spatial scales. Continental paleoclimatic records not only provide information about past climate changes at scales relevant to human activities, they demonstrate how the components of the landscape with which humans interact (such as vegetation, streams, and lakes) respond to perturbations, climatic or otherwise.

High temporal resolution and continuity are particularly important aspects of records for lacustrine sediments. Variousclimatic proxies contained in the sediment must be sensitive to some aspect of climate, and proxies need to be quantitatively calibrated against modern conditions or historical records.

Based on this discussion of the organizational, operat-ional, analytical, and data aspects of lake drilling projects, the following evaluation criteria are recommended:
· Quality of potential paleoclimate records, dating control, and scientific importance of the site;
· Adequate preliminary data and site surveys
· A defined organizational structure.
· Efficient use of existing equipment or construction of new equipment.
· Arrangements for obtaining and preserving cores in as high-quality a condition as possible;
· Recommendations for "standard" core analyses including non-destructive and pre-sampling measurements;
· Sampling and analysis protocols that include ALL relevant dating and climate-proxy analyses;
· Adequate core storage and archiving facilities;
· Protocols for data dissemination, core archiving, and sample availability to the scientific community, and publication of results.

Paleoclimate records derived from continental sediments are clearly a high priority for climate and global change issues. Three types of long paleoclimate records form the primary basis for true global paleoclimate reconstruction: marine deposits, ice cores, and lacustrine sediments. Compared to the other two, lacust-rine paleoclimate records are underdeveloped. Drilling and coring projects focused on paleoclimate records derived from lake sediments would benefit from an approach more like their marine and ice-core analogs than has been their tradition. They need to be larger, broader, and better organized if the full potential of lacustrine records of paleoclimate is to be fully realized.

9. ACKNOWLEDGMENTS

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The original impetus for the Workshop and much support came from Herman Zimmerman, then Co-Director of PAGES. J. Negendank organized all of the local arrangements for the Workshop, and liaisons to ICDP were provided by I. MacGregor and R. Emmmerman.

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0. TABLE OF CONTENTS **10. REFERENCES**

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10. REFERENCES CITED

- **Ager, T. (1996)** The U.S.Geological Survey global change drilling project at Fort Yukon, Alaska, 1994. USGS Open-File Report, in press.

- **Anderson, R. Y. (1993)** The Varve Chronometer in Elk Lake: Record of Climatic Variability and Evidence for Solar/Geomagnetic- ^{14}C-Climate Connection. In Bradbury, J. P. and Dean, W. E. (eds.) Elk Lake, Minnesota: Evidence for Rapid Climate Change in the North-Central United States. Geological Society of America Special Paper 276, 45-68.
- **Anderson, R. Y. and Dean, W. E. (1988)** Lacustrine varve formation through time. In Gray, J. (ed.) Aspects of Freshwater Paleoecology and Biogeography. Elsevier, 215-236.
- **Andrews, J. T. and Jennings, A.E. (1987)** Influence of sediment source and type on the magnetic susceptibility of fiord and shelf deposits, Baffin Island and Baffin Bay, N. W. T. Can. J. Earth Sci. 24, 1386-1401.
- **Andrews, J. T., Geirsdottir, A., and Jennings, A. E. (1989)** Spatial and temporal variations in clay- and silt-size mineralogies of shelf and fiord cores, Baffin Island. Cont. Shelf Res. 9, 445-463.
- **Appleby, P.G. and Oldfield, F. (1992)** Application of ^{210}Pb to sediment studies. In Ivanovich, M. and Harmon, R. (eds.) Uranium Series Disequilibrium: Application to Earth, Marine, and Environmental Studies. Clarendon Press, Oxford, 731-738.
- **Appleby, P.G., Nolan, P.J., Oldfield, F., Richardson, N., and Higgitt, S.R. (1988)** ^{210}Pb dating of lake sediments and ombrotrophic peats by gamma assay. The Science of the Total Environment 69, 157-177.
- **Baksi, A.K., Hsu, V., McWilliams, M., and Farrar, E. (1992)** ^{40}Ar/ ^{39}Ar dating of the Brunhes-Matuyama geomagnetic field reversal. Science 256, 356.
- **Barranco, F. T. Jr., Balsam, W. L., and Deaton, B. C. (1989)** Quatitative reassessment of brick-red lutites: Evidence from reflectance spectrophotometry. Marine Geology 89, 299-314.
- **Bartlein, P. J. and Whitlock, C. (1993)** Paleoclimatic Interpretation of the Elk Lake Pollen Record. In Bradbury, J. P. and Dean, W. E. (eds.) Elk Lake, Minnesota: Evidence for Rapid Climate Change in the North-Central United States. Geological Society of America Special Paper 276, 275-294.
- **Bartlein, P. J., Prentice, I. C., and Webb, T. III (1986)** Climatic response surfaces from pollen data for some eastern North American taxa. Journal of Biogeography 13, 35-57.
- **Barton, C. E. and Burden, F. R. (1979)** Modifications to the Mackereth corer. Limnology and Oceanography 24, 977-983.
- **Bates, A. L., Spiker, E. C., Orem, W. H., and Burnett, W. C., (1993)** Speciation and isotopic composition of sulfur in sediments from Jellyfish Lake, Palau. Chem. Geol. 106, 63-76.
- **Bates, A. L., Spiker, E. C., Hatcher, P. G., Scott, A. S., and Weintraub, V. C. (1995)** Sulfur geochemistry of organic-rich sediments from Mud lake, Florida, U. S. A. Chem. Geol. 121, 245-262.
- **Battarbee, R. W. (1986)** Diatom analysis. In Berglund, B. E. (ed.) Handbook of Holocene Palaeoecology and Palaeohydrology. J. Wiley, New York, 527-570.
- **BDP-93 Baikal Drilling Project Members (1996)** Preliminary results of the first drilling on Lake Baikal, Buguldeika site, south-eastern Siberia. Quaternary International, in press.
- **Begét, E., Machida, H. and Lowe, D. J. (1996)** Climatic Impact of Explosive Volcanism:

Recommendations for Research. PAGES Workshop Report, Series 96-3

- **Bengtsson, L and Enell, M. (1986)** Chemical analysis. In Berglund, B. E. (ed.) Handbook of Holocene Paleoecology and Paleohydrology. J. Wiley, Chichester.
- **Berger, G. W. (1988)** TL dating studies of tephra, loess, and lacustrine sediments. Quaternary Science Reviews 7, 295-304.
- **Berglund, B. E. (ed.) (1986)** Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley and Sons, Chichester.
- **Berner, R. A. (1984)** Sedimentary pyrite formation: An update. Geochim. Cosmochim. Acta, 48, 605-615.
- **Birks, H. H. (1980)** Plant macrofossils in Quaternary lake sediments. Arch. Hydrobiol. Beih. Ergbn. Limnol. 16, 1-60.
- **Bischoff, J. L., Rosenbauer, R. J., and Smith, G. I. (1985)** Uranium-series dating of sediments from Searles Lake: Differences between continental and marine climate records. Science 227, 1222-1224.
- **Bond, G. C. and Lotti, R. (1995)** Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation. Science 267, 1005-1010.
- **Boyce, R. E. (1976)** Appendix I: Definitions and laboratory techniques of compressional sound velocity parameters and water content, wet-bulk density, and porosity parameters by gravimetric and gamma-ray attenuation techniques. Initial Reports of the Deep Sea Drilling Project 33, 931-978
- **Bradbury, J. Platt (1988)** Fossil diatoms and Neogene paleolimnology. In Gray, J. (ed.) Aspects of Freshwater Paleoecology and Biogeography. Elsevier, 299-316.
- **Bradbury, J. P. and Dieterich-Rurup, K. V. (1993)** Holocene diatom paleolimnology of Elk Lake, Minnesota. in Bradbury, J. Platt and Dean, Walter E. (eds.) Elk Lake, Minnesota: Evidence for Rapid Climate Change in the North-Central United States. Geological Society of America Special Paper 276, 215-238.
- **Bradbury, J. P., Dean, W. E., and Anderson, R. Y. (1993)** Holocene Climatic and Limnologic History of the North-Central United States as Recorded in the Varved Sediments of Elk Lake, Minnesota: A Synthesis. In Bradbury, J. P. and Dean, W. E. (eds.) Elk Lake, Minnesota: Evidence for Rapid Climate Change in the North-Central United States. Geological Society of America Special Paper 276, 309-328.
- **Bradley, R.S. (ed.) (1991)** Global changes of the past. UCAR/Office for Interdisciplinary Earth Studies, Boulder, Colorado, 514 pp.
- **Broecker, W.S. (1994)** Massive iceberg discharges as triggers for global climate change. Nature 372, 421-424.
- **Broecker, W. S. (1996)** Glacial climate in the tropics. Science 272, 1902-1904.
- **Brown, S.R., McIntosh, H.J., and Smol, J.P. (1984)** Recent paleolimnology of a meromictic lake: Fossil pigments of photosynthetic bacteria. Verh. Internat. Verein. Limnol. 22, 1357-1360.
- **Brown, T.A., Nelson, D.E., Mathewes, R.W., Vogel, J.S. and Southon, J.R. (1989)** Radiocarbon dating of pollen by accelerator mass spectrometry. Quaternary Research 32, 205-212.
- **Champion, D.E., Lanphere, M.A., and Kuntz, M.A. (1988)** Evidence for a new geomagnetic reversal from lava flows in Idaho: Discussion of short polarity reversals in the Brunhes and late Matuyama polarity chrons. Journal of Geophysical Research 93, B10, 11667-11680.
- **COHMAP Members (1988)** Climatic changes of the last 18,000 years: Observations and model simulations. Science 241, 1043-1052.
- **Collinson, D.W. (1983)** Methods in rock magnetism and palaeomagnetism, techniques and instrumentation. Chapman and Hall, New York, 503 pp.
- **Colman, S.M., Jones, G.A., Forester, R.M., and Foster, D.S. (1990)** Holocene paleoclimatic evidence and sedimentation rates from a core in southwestern Lake Michigan. Journal of Paleolimnology 4, 269-284.
- **Colman, S. M., Peck, J. A., Karabanov, E. B., Carter, S. J., King, J. W., and Williams, D. F. (1995)** Continental climate response to orbital forcing: The diatom paleoproductivity record from

Lake Baikal, Siberia. Nature 378, 769-771.

- **Colman, S.M., Jones, G.A. Rubin, Meyer, King, J.W., Peck, J.A., and Orem, W.H. (1996)** AMS radiocarbon analyses from Lake Baikal, Siberia: Challenges of dating sediments from a large, oligotrophic lake. Quaternary Geochronology (Quaternary Science Reviews) 15, 669-684.
- **Creer, K. M. and Morris, A. (1996)** Proxy-climate and geomagnetic palaeointensity records extending back to ca. 75,000 BP derived from sediments cored from Lago Grande di Monticchio, southern Italy. Quaternary Science Reviews 15, 167-188.
- **Dean, W. E., Gardner, J. V., and Anderson, R. Y. (1994)** Geochemical evidence for enhanced preservation of organic matter in the oxygen minimum zone of the continental margin of northern California during the late Pleistocene. Paleoceanography 9, 47-61.
- **DeDeckker, P. (1988)** An account of the techniques using ostracodes in palaeolimnology in Australia. In Gray, J. (ed.) Aspects of Freshwater Paleoecology and Biogeography. Elsevier, New York, 463-476.
- **DeDeckker, P. and Forester, R. M. (1988)** The use of ostracodes to reconstruct continental paleoenvironmental records. In DeDeckker, P., Colin, J. P., and Peypouquet, J. P. (eds.) Ostracoda in the Earth Sciences. Elsevier, New York, 175-199.
- **Delorme, L. D. (1989)** Methods in Quaternary Ecology No. 7. Freshwater Ostracodes. Geosciences Canada 16, 85-90.
- **DeMaster, David J. (1981)** The supply and accumulation of silica in the marine environment. Geochimica et Cosmochimica Acta 45, 1715-1732.
- **Dixon, F.S. and Karig, D. (1969)** The Scripps Institute of Oceanography Marine Technician's HandbookPiston Coring. Institute of Marine Resources Technical Report 38, Sea Grant Publication 19, La Jolla, California.
- **Duplessy, J-C., and Overpeck, J.T. (1996)** The PAGES/CLIVAR Intersection. Report of a joint IGBP-WCRP Workshop, Venice, Italy. PAGES Core Project Office, Bern, Switzerland, 48 pp..
- **Dupont, L. M. (1993)** Vegetation zones in NW Africa during the Brunhes Chron reconstructed from marine palynological data. Quaternary Science Reviews 12, 189-202.
- **Eddy, J.A. (ed.) (1992)** Past Global Changes Project: Proposed Implementation Plans for Research Activities. IGBP Report No. 19, Stockholm, 112 pp.
- **Edgington, D. N., Robbins, J. A., Colman, S. M., Orlandini, K. A., and Gustin, M.-P. (1996)** Uranium-series disequilibrium, sedimentation, diatom frustules, and paleoclimate change in Lake Baikal. Earth and Planetary Science Letters, 142, 29-42.
- **Engel, M.H. and Macko, S.A. (1993)** Organic Geochemistry: Principles and Applications. Plenum Press, New York, 861 pp.
- **Engstrom, D. R. and Nelson, S. R. (1991)** Paleosalinity from trace metals in fossil ostracodes compared with observational records at Devils Lake, North Dakota, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 83, 295-312.
- **Engstrom, D. R. and Wright, H. E. (1984)** Chemical stratigraphy of lake sediments as a record of environmental change. In Haworth, E. Y. and Lund, J. W. G. (eds.) Lake Sediments and Environmental History. Leicester University Press, 11-67.
- **Eugster, H. P. and Kelts, K. (1983)** Lacustrine chemical sediments. In Goudie, A. (ed.) Chemical sediments and geomorphology: Precipitates and residua in the near-surface environment. Academic Press, London, 321-368.
- **Faegri, K. and Iverson, J. (1989)** Appendix A. In Faegri, K., Kaland, P. E., and Krzywinski, K (eds.) Textbook of Pollen Analysis. Blackwell, New York, 69-89.
- **Forester, R. M. (1991)** Ostracode assemblages from springs in the western United States: Implications for paleohydrology. Memoirs of the Entomological Society of Canada 155, 181-201.
- **Forester, R.M., Colman, S.M., Reynolds, R.L., Jones, G.A., Keigwin, L.D., and Foster, D.S. (1994)** The limnological and climate history of Lake Michigan from ostracode, stable-isotope, and magnetic susceptibility records. Journal of Great Lakes Research 20, 93-107.
- **Fritz, P. and Fontes, J.C. (eds.) (1980)** Handbook of Environmental Isotope Geochemistry.

Elsevier, Amsterdam.

- **Gasse, F. and Fontes, J.-C. (1989)** Palaeoenvironments and palaeohydrology of a tropical closed lake (Lake Asal, Djibouti) since 10,000 yr B.P. Palaeogeogr. Paleoclim. Paleoecol. 69, 67-102.
- **Godfrey-Smith, D. I., Huntley, D. J., and Chen, W.-H. (1988)** Optical dating studies of quartz and feldspar sediment extracts. Quaternary Science Reviews 7, 373-380.
- **Goslar, T., Arnold, M., Bard, E., Kuc, T., Pazdur, M. F., Ralska-Jasiewiczowa, M., Rózanski, K., Tisnerat, N., Walanus, A., Wicik, B., and Wieckowski, K. (1995)** High concentration of atmospheric $_{14}$C during the Younger Dryas cold episode. Nature 377, 414-417.
- **Grün, Rainer (1989)** Electron spin resonance (ESR) dating. Quaternary International 1, 65-109.
- **Guilizzoni, P. and Lami, A. (1992)** Historical records of changes in the chemistry and biology of Italian Lakes. Mem. Ist. Ital. Idrobiol. 50, 61-77.
- **Guiot, J. (1987)** Late Quaternary climatic change in France estimated from multivariate pollen time series. Quaternary Research 28, 100-118.
- **Guiot, J., Harrison, S. P., and Prentice, I. C. (1993)** Reconstruction of Holocene precipitation patterns in Europe using pollen and lake-level data. Quaternary Research 40, 139-149.
- **Hajdas, I., Zolitschka, B., Ivy-Ochs, S. D., Beer, J., Bonani, G., Leroy, S. A. G., Negendank, J. W., Ramrath, M., and Suter, M. (1995)** AMS radiocarbon dating of annually laminated sediments from Lake Holzmaar, Germany. Quaternary Science Reviews 14, 137-143.
- **Halfman, J. D. and Johnson T.C. (1984)** Enhanced atmospheric circulation over North America during the early Holocene -- Evidence from Lake Superior. Science 224, 61-63.
- **Harrison, S. P. and Digerfeldt, G. (1993)** European lakes as palaeohydrological and palaeoclimatic indicators. Quaternary Science Reviews 12, 233-248.
- **Harrison, S. P., Kutzbach, J. E., Prentice, I. C., Behling, P. J., and Sykes, M. T. (1995)** The response of Northern Hemisphere extratropical climate and vegetation to orbitally induced changes in insolation during the last interglaciation. Quaternary Research 43, 174-184.
- **Harrison, Sandy P. (1989)** Lake levels and climatic change in eastern North America. Climate Dynamics 3, 157-167.
- **Haworth, E. Y (1984)** In Haworth, E. Y. and Lund J. W. G. (eds.) Lake Sediments and Environmental History. University of Minnesota Press, Minneapolis, 165-190.
- **Heaton, T.H.E., Holmes, J.A., and Bridgewater, N. D. (1995)** Carbon and oxygen isotope variations among lacustrine ostracods: Implications for palaeoclimatic studies. The Holocene 5, 428-434.
- **Hedges, J. I. and Stern, J. H. (1984)** Carbon and nitrogen determinations of carbonate-containing solids. Limnology and Oceanography 29, 657-663.
- **Hollander, D. J., McKenzie, J. A., and Lo ten Haven, H. (1992)** A 200 year sedimentary record of progressive eutrophication in Lake Greifen (Switzerland): Implications for the origin of organic-carbon-rich sediments. Geology 20, 825-828.
- **Holmes, J. A. (1996)** Trace-element and stable isotope geochemistry of non-marine ostracod shells in Quaternary palaeoenvironmental reconstruction. Journal of Paleolimnology 15, 223-235.
- **Hong, S., Candelone, J.-P., Patterson, C. C., and Boutron, C. F. (1994)** Greenland ice evidence of hemispheric lead pollution two millenia ago by Greek and Roman Civilizations. Science 265, 1841-1843.
- **Hooghiemstra, H., Melice, J. L., Berger, A., and Shackleton, N. J. (1993)** Frequency spectra and paleoclimate variability of the high-resolution 30-1450 ka Funza I pollen record (eastern Cordillera, Columbia). Quaternary Science Reviews 12, 141-156.
- **Horie, S. (1987)** History of Lake Biwa. Contribution 553, Institute of Paleolimnology and Paleoenvironment on Lake Biwa, Kyoto Univeristy, Kyoto, Japan, 242 pp.
- **Horie, S. (1991)** Die Geschichte des Biwa-Sees in Japan. Universitaetsverlag Wagner, Innsbruck, Austria, 346 pp.
- **Hostetler, S.W. and Benson, L.V. (1994)** Stable isotopes of oxygen and hydrogen in the Truckee River - Pyramid Lake surface-water system. Limnology and Oceanography 39, 356-364.

- **Hughen, K. A., Overpeck, J. T., Peterson, L. C., and Trumbore, S. (1996)** Rapid climate changes in the tropical Atlantic region during the last deglaciation. Nature 380, 51-54.
- **Imbrie, J., Hays, J. D., Martinson, D. G., McIntyre, A., Mix, A. C., Morley, J. J., Pisias, N. G., Prell, W. L., and Shackleton, N. J. (1984)** The orbital theory of Pleistocene climate--support from a revised chronology of the marine ^{18}O record. In Berger, A. L. and others (eds.) Milankovitch and Climate, Part 1. D. Reidel Pubishing Co., Boston, 269-305.
- **Johnson, T.C. (ed.) (1993)** An International Decade for East African Rift Lakes (IDEAL). PAGES Workshop Report 93-2, 39 pp.
- **Jones, B. F. and Bowser, C. J. (1978)** The mineralogy and related chemistry of lake sediments. In Lerman, A. (ed.) Lakes: Chemistry, Geology, Physics. Springer-Verlag, New York, 179-235.
- **Kelts, K and Hsü, K. J. (1978)** Freshwater carbonate sedimentation. In Lerman, A. (ed) Lakes, Physics, Chemistry, Geology. Springer Verlag, New York, 295-323.
- **Kelts, K. and Talbot, M. (1990)** Lacustrine Carbonates As Geochemical Archives of Environmental Change and Biotic/Abiotic Interactions. Large Lakes, Ecological Structure and Function 288-315.
- **Kelts, K., Briegel, U., Ghilardi, K., and Hsu, K. (1986)** The limnogeology-ETH coring system. Schweiz. Z. Hydrol. 48, 104-115.
- **Kerr, S. J., Stanistreet, I. G., and Partridge, T. C. (1993)** The sedimentary facies record from the Pretoria Saltpan crater. South African Journal of Science 89, 372-374.
- **Killops S.D. and Killops V.J. (1983)** An Introduction to Organic Geochemistry. Longman Scientific and Technical, UK, 265 pp.
- **King, J.W., Banerjee, S.K., and Marvin, J. (1983)** A new rock magnetic approach to selecting samples for geomagnetic paleointensity studies: Application to paleointensity for the last 4000 years. Journal of Geophysical Research 88, 5911-5921.
- **King, J. W. and Channell, J. E. T. (1991)** Sedimentary magnetism, environmental magnetism, and magnetostratigraphy. Rev. Geophys. Suppl. 358-370.
- **Knox, J. C. (1985)** Responses of floods to Holocene climatic change in the upper Mississippi Valley. Quaternary Research 23, 287-300.
- **Krishnamurthy, R. V., Syrup, K. A., Baskaran, M., and Long, A. (1995)** Late glacial climate record of midwestern United States from the hydrogen isotope ratio of lake organic matter. Science 269, 1565-1567.
- **Lao, Y. and Benson, L. (1988)** Uranium-series age estimates and paleoclimatic significance of Pleistocene tufas from the Lahontan Basin, California and Nevada. Quaternary Research 30, 165-176.
- **Leavitt, P.R. (1993)** A review of the factors that regulate carotenoid and chlorophyll deposition and fossil pigment abundance. Journal of Paleolimnology 9, 109-127
- **Lewis, D. W. (1984)** Practical Sedimentology. Hutchinson Ross Publishing Co., Stroudsburg, PA, 22 pp.
- **Lister, G. S. (1988)** Stable isotopes from lacustrine Ostracoda as tracers for continental palaeoenvironments. In DeDeckker, P., Colin, J. P., and Peypouquet, J. P. (eds.) Ostracodea in the Earth Sciences. Elsevier, Amsterdam, 20-.
- **Lister, G. S. (1989)** Reconstruction of palaeo air temperature changes from oxygen isotope records in Lake Zürich: The significance of seasonality. Eclogae geol. Helv. 82, 219-234,
- **Livingston, D. (1965)** The use of filiment tape in raising long cores from soft sediment. Limnology and Oceanography 12, 346-348.
- **Lotter, A. F. (1991)** Absolute dating of the late-glacial period in Switzerland using annually laminated sediments. Quaternary Research 35, 321-330.
- **Lottermoser, B. G., Oberhdnsli, R., Zolitschka, B., Negendank, J. F. W., Schultz, U., and Boenecke, J. (1993)** Environmental geology and geochemistry of lake sediments (Holzmaar, Eifel, Germany) Lectures Notes in Earth Sciences. In Negendank, J. F. W. and Zolitschka, B. (eds.) Paleolimnology of European maar lakes. Springer-Verlag, Berlin, Germany, 305-316.

- **Lövlie, R. and Leroy, S. (1995)** Magnetostratigraphy of Lower Pleistocene Banyoles paleolake carbonate sediments from Catalonia, NE-Spain: Evidence for relocation of the Cobb Mountain sub-chron. Quaternary Science Reviews 14, 473-486.
- **Lund, S.P. (1993)** Paleomagnetic secular variation. Trends in Geophysical Research 2, 423-438.
- **MacDonald, G. M., Edwards, T. W. D., Moser, K. A., Pienitz, R., and Smol, J. P. (1993)** Rapid response of treeline vegetation and lakes to past climatic warming. Nature 361, 243-246.
- **Mackereth, F. J. H. (1958)** A portable core sampler for lake deposits. Limnology and Oceanography 3, 181-191.
- **Mackereth, F. J. H. (1966)** Some chemical observations on post-glacial sediments. Philosophical Transactions of the Royal Society B250, 165-213.
- **Mackereth, F. J. H. (1969)** A short core sampler for subaqueous deposits. Limnology and Oceanography 14, 145-151.
- **Markgraf, V. and Kenny, R. (1996)** Character of rapid vegetation and climate change during the late-glacial in southermost South America. In Huntley, B., Cramer, W., Morgan, A. V., Prentice, H. C., and Allen, J. R. M. (eds.) Past and Future Rapid Environmental Changes: The Spatial and Evolutionary Responses of Terrestrial Biota. Springer Verlag, Berlin, 81-90.
- **McKenzie, J. A. (1985)** Carbon Isotopes and Productivity in the Lacustrine and Marine Environment. In Stumm, W. (ed.) Chemical Processes in Lakes. Wiley, New York, 99-118.
- **McManus, D. A. (1991)** Suggestions for authors whose manuscripts include quantitative clay mineral analysis by X-ray diffraction. Mar. Geol. 98, 1-5.
- **Merkt, J. and Streif, H. (1970)** Stechrohr-Bohrgeraete fuer limnische und marine Lockersedimente. Geol. Jb. 88, 137-148.
- **Meyers, P.A. and Ishiwatari, R. (1993)** The early diagenesis of organic matter in lacustrine sediments. In Engels, M.H. and Macko, S.A, (eds.) Organic Geochemistry: Principles and Applications, Plenum Press, New York,185-209.
- **Moore, P. D., Webb, J. A., and Collinson, M. E. (1991)** Pollen Analysis. Blackwell, Oxford.
- **Moore, T. C. Jr., Rea, D. K., Mayer, L. A., Lewis, C. F. M., and Dobson, D. M. (1994)** Seismic stratigraphy of Lake Huron-Georgian Bay and post-glacial lake level history. Canadian Journal of Earth Sciences 31, 1606-1617.
- **Mortlock, M. A. and Froelich, P. N. (1989)** A simple method for rapid determination of biogenic opal in pelagic marine sediments. Deep-Sea Research 36, 1415-1426.
- **Oeschger, H. and Eddy, J.A., (1989)** Global Changes of the Past. IGBP Report No. 6, Stockholm, 39 p.
- **Orem, William H., Colman, Steven M., and Lerch, Harry E. (1996)** Lignin Phenols in sediments of Lake Baikal, Siberia: Application to Paleoenvironmental studies. Organic Geochemistry, in press.
- **Overpeck, J. T., Prentice, I. C., and Webb, T. III (1985)** Quantitative interpretation of fossil pollen spectra: Dissimilarity coefficients and the method of modern analogs. Quaternary Research 23, 87-108.
- **Pachur, Denner, and Walter (1984)** A freezing device for sampling the sediment-water interface of lakes. Catena 11, 65-70.
- **PAGES (1995)** Paleoclimates of the Northern and Southern Hemispheres; The PANASH Project, Pole-Equator-Pole Transects. PAGES Report 95-1, 92 pp.
- **PALE Steering Committee (1993)** Research protocols for PALE. Paleoclimate of Arctic lakes and estuaries. PAGES Workshop Report 94-1, 53 pp
- **Partridge, T. C. and Watt, I. B. (1991)** The stratigraphy of the Sterkfontein hominid deposit and its relationship to the underground cave system. Palaeont. Afr. 28, 35-40.
- **Partridge, T. C., Kerr, S. J., Metcalfe, S. E., Scott, L., Talma, A. S., and Vogel, J. C. (1993)** The Pretoria Saltpan: a 200,000 year Southern African lacustrine sequence. Palaeogeography, Palaeoclimatology, Palaeoecology 101, 317-337.
- **Peck, J. A., King, J. W., Colman, S. M., and Kravchinsky, V. A. (1994)** A rock-magnetic record

from Lake Baikal, Siberia: Evidence for late Quaternary climate change. Earth and Planetary Science Letters 122, 221-238.

- **Peck, J. A., King, J. W., Colman, S. M., and Kravchinsky, V. A. (1996)** An 84-kyr paleomagnetic record from sediments of Lake Baikal, Siberia. Journal of Geophysical Research 101, B5, 11,365-11,385.
- **Peglar, S. (1993)** The mid-Holocene *Ulmus* decline at Diss Mere, Norfolk, UK: a year-by-year pollen stratigraphy from annual laminations. The Holocene, 31, 1-13.
- **Peters, K.E. and Moldowan, J.M (1993)** The biomarker guide: Interpreting molecular fossils in petroleum and ancient sediments. Prentice Hall, New Jersey, 363 pp.
- **Pilcher, J.R. and Hall, V.A. (1996)** Tephrochronological studies in Northern England. The Holocene 6, 100-105.
- **Prahl, F.G., Ertel, J.R., Goni, M.A., Sparrow, M.A. and Eversmeyer, B. (1994)** Terrestrial organic carbon contributions to sediments on the Washington margin. Geochim. Cosmochim. Acta. 58, 3035-3048.
- **Rea, D. K. and Colman, S. M. (1995)** Radiocarbon ages of pre-bomb clams and the hard-water effect in Lakes Michigan and Huron. Journal of Paleolimnology 14, 89-91.
- **Reasoner, M. A. (1993)** Equipment and procedure improvements for a lightweight, inexpensive, percussion core sampling system. Journal of Paleolimnology 8, 273-281.
- **Renberg, I. and Hansson, H. (1993)** A pump freeze corer for recent sediments. Limnology and Oceanography 38, 1317-1321.
- **Renberg, I., Persson, M. W., and Emteryd, O. (1994)** Pre-industrial atmospheric lead contamination detected in Swedish lake sediments. Nature 368, 323-326.
- **Reynolds, R. L. and King, J. W. (1995)** Magnetic records of climate change. Reviews of Geophysics, Supplement, 101-110.
- **Rieley, G., Collier, R.J, Jones, D.M. and Eglinton, G. (1991)** The biogeochemistry of Ellesmere Lake, U.K., - I: source correlation of leaf wax inputs to the sedimentary lipid record. Org. Geochem. 17, 901-912.
- **Robbins, J. A. (1978)** Geochemical and geophysical applications of radioactive lead. In Nriagu, J. O. (ed.) Biogeochemistry of lead in the environment. Elsevier Scientific Publ., Amsterdam, 285-293.
- **Rosefelder, A.M. and Marshall, N.F. (1967)** Obtaining large, undisturbed, and oriented samples in deep water. In Richards, A.F. (ed.) Marine Geotechniques. University of Illinois Press, Urbana, 243-263.
- **Saarnisto, M. (1986)** Annually laminated lake sediments. In Berglund, B. (ed.) Handbook of Holocene Paleoecology and Paleohydrology. Wiley & Sons, 343-370.
- **Sanger, J.E. (1988)** Fossil pigments in paleoecology and paleolimnology. Paleogeography, Paleoclimatology, and Paleoecology 62, 343-359.
- **Santer, B. D., Taylor, K. E., Wigley, T. M. L., Johns, T. C., Jones, P. D., Karoly, D. J., Mitchell, J. F. B., Oort, A. H., Penner, J. E., Ramaswamy, V., Schwarzkopf, M. D., Stouffer, R. J., and Tett, S. (1996)** A search for human influences on the thermal structure of the atmosphere. Nature 382, 39-46.
- **Sarna-Wojcicki, A. M. and Davis, J. O. (1991)** Quaternary tephrochronology. In Morrison, R. B. (ed.) Quaternary Non-Glacial Geology: Conterminous United States. Geological Society of America, Decade of North American Geology, Vol. K-2, Boulder, Colorado, 93-116.
- **Schaaf, M. and Thurow, J. (1994)** A fast and easy method to derive hightest-resolution time-series datasets from drillcores and rock samples. Sedimentary Geology 94, 1-10.
- **Schelske, C.L. and Hodell, D.A. (1995)** Using carbon isotopes of bulk sedimentary organic matter to reconstruct the history of nutrient loading and eutrophication in Lake Erie. Limnol. Oceanogr. 40, 918-929.
- **Schneider R. and Tobolski, K. (1985)** Lago di Ganna - Lateglacial and Holocene environments of a lake in the southern Alps. Diss. Botany 87, 229-271.

- **Schwalb, A., Lister, G. S., and Kelts, K. (1994)** Ostracode carbonate d $_{18}$O-and d $_{13}$C-signatures of hydrological and climatic changes affecting Lake Neuchâtel, Switzerland, since the latest Pleistocene. Journal of Paleolimnology 11, 3-17.
- **Simola, H. (1981)** Sedimentation in a eutrophic stratified lake in S. Finland. Ann. Bot. Fennici 18, 23-36.
- **Smith, A. J. (1993)** Lacustrine ostracodes as hydrochemical indicators in lakes of the north-central United States. Journal of Paleolimnology 8, 121-134.
- **Spiker, E. C. and Bates, A. L. (1993)** Sulfur isotope effects of Late Quaternary climate change in lake Baikal, Siberia. Russian Geology and Geophysics 34, 84-88.
- **Stein, R. (1991)** Accumulation of organic carbon in marine sediments. Springer-Verla, Berlin, 34, 217 pp.
- **Stuiver, M., Braziunas, T. F., Becker, B., and Kromer, B. (1991)** Climatic, solar, oceanic, and geomagnetic influences on late-glacial and Holocene atmospheric $_{14}$C/ $_{12}$C change. Quaternary Research 35, 1-24.
- **Stuiver, M. (1970)** Oxygen and carbon isotop ratios of freshwater carbonates as climatic indicators. Journal of Geophysical Research 75, 5247-5257.
- **Stute, M., Forster, M., Frischkorn, H., Serejo, A., Clark, J.F., Schlosser, P., Broecker, W.S., and Bonani, G. (1995)** Cooling of tropical Brazil (5 $_{o}$C) during the last glacial maximum. Science 269, 379-383.
- **Syvitski, J. P. M (ed.) (1991)** Principles, Methods of Application of Particle Size Analysis. Cambridge University Press, New York.
- **Talbot, M. R. (1990)** A review of the palaeohydrological interpretation of carbon and oxygen isotopic ratios in primary lacustrine carbonates. Chem. Geol., Isot. Geosci. Sect. 80, 261-279.
- **Thetford, R. D., D'Arrigo, R. D., and Jacoby, G. C. (1991)** An image analysis system for determining densitometric and ring-width time series. Can. J. For. Res. 21, 1544-1549.
- **Thompson, L. G. Mosley-Thompson E. Davis M. E. Lin P. N. Henderson K. A. Cole-Dai J. Bolzan J. F. Liu K. b. (1995)** Late glacial stage and Holocene tropical ice core records from Huascarán, Peru. Science 269, 46-50.
- **Thompson, R. (1984)** A global review of paleomagnetic results from wet lake sediments. In Hayworth, E. Y. and Lund, J. W. G. (eds.) Lake Sediments and Environmental History. University of Minnesota Press, Minneapolis, Minnesota, 145-164.
- **Thompson, R. and Oldfield, F. (1986)** Environmental magnetism. Allen & Unwin, London, 227 pp.
- **Thunell, R., Pride, C., Tappa, E., and Muller-Karger, F. (1993)** Varve formation in the Gulf of California: Insights from time series sediment trap sampling and remote sensing. Quaternary Science Reviews 12, 451-464.
- **Tobias, P., Vogel, J., Oschadleus, H. D., Partridge, T. C., and McKee, J. K. (1993)** New isotopic and sedimentological measurements of the Thabaseek deposits (South Africa) and the dating of the Taug Hominid. Quaternary Research 40, 360-367.
- **Troels-Smith, J. (1955)** Characterisation of unconsolidated sediments. Geological Survey of Denmark IV series 3, 10, 1-73.
- **Tuttle, M. L., Goldhaber, M. B., and Williamson, D.L. (1986)** An analytical scheme for determining forms of sulphur in oil shales and associated rocks. Talanta 33, 953-961.
- **Tuttle, M. L., Rice, A. C., and Goldhaber, M. B. (1990)** Geochemistry of organic and inorganic sulfur in ancient and modern lacustrine environments: Case studies of freshwater and saline lakes. In Orr, W. L. and White, C. M. (eds) Geochemistry of Sulfur in Fossil Fuels. Am. Chem. Soc. Symp. Ser. 393, 231-242.
- **Vairavamurhty, M., and Schoonen, M. (eds.) (1994)** Geochemical Transformations of Sedimentary Sulfur. ACS Symposium Series 612, American Chemical Society, Washington D.C., 467 pp.
- **Van Geel, B., Coope, G. R., and van der Hammen, T. (1989)** Palaeoecology and stratigraphy of

the Lateglacial type section at Usselo (The Netherlands). Rev. of Palaeobot. and Palynol. 60, 25-129.

- **Wasylikowa, K. (1986)** Analysis of fossil fruits and seeds. In Berglund, B. (ed.) Handbook of Holocene Palaeoecology and Palaeohydrology. Wiley & Sons, 571-590.
- **Watts, W. A., Allen, J. R. M., Huntley, B., and Fritz, S. C. (1996)** Vegetation history and climate of the last 15,000 years at Laghi di Monticchio, southern Italy. Quaternary Science Reviews 15, 113-132.
- **Webb, R. S., Anderson, K. H., and Webb, T. III (1993)** Pollen response-surface estimates of late Quaternary changes in the moisture balance of the northeastern United States. Quaternary Research 40, 213-227.
- **Weliky, K., Suess, E., Ungerer, C. A., Muller, P. J., and Fischer, K. (1983)** Problems with accurate carbon measurements in marine sediments and particulate matter in seawater: A new approach. Limnology and Oceanography 28, 1252-59.
- **Westgate, J.A. and Gorton, M.P. (1981)** Correlation techniques in tephra studies. In Self, S. and Sparks, R.S.J., editors, Tephra Studies, Reidel, Dordrecht, 73-94.
- **Whitlock, C., Bartlein, P. J., and Watts, W. A. (1993)** Vegetation history of Elk Lake. In Bradbury, J. Platt and Dean, Walter E. (eds.) Elk Lake, Minnesota: Evidence for Rapid Climate Change in the North-Central United States. Geological Society of America Special Paper 276, 251-274.
- **Williams, T., Thouveny N., and Creer K.M. (1996)** Palaeoclimatic significance of the 300 ka mineral magnetic record from the sediments of Lac du Bouchet, France. Quat. Sc. Rev. 15, 223-236.
- **Winograd, I. J., Coplen, T. B., Landwehr, J. M., Riggs, A. C., Ludwig, K. R., Szabo, B. J., Kolesar, P. T., and Revesz, K. M. (1992)** Continous 500,000-year climate record from vein calcite in Devils Hole, Nevada. Science 258, 255-260.
- **Wright H., Cushing, E., and Livingstone D. (1965)** Coring devices for lake sediments. In Kummel, B. and Raup, D. (eds.) Handbook of palaeontological techniques. Freeman, San Francisco, California, 494-520.
- **Wright, H. E. Jr. (1967)** A square-rod piston sampler for lake sediments. Journal of Sedimentary Petrology 975-976.
- **Wright, H. E. Jr. (1980)** Cores of soft lake sediments. Boreas 9, 107-114.
- **Wright, H. E. Jr. (1991)** Coring tips. Journal of Paleolimnology 6, 37-49.
- **Wright, H. E. Jr. (1992)** Patterns of Holocene Climatic Change in the Midwestern United States. Quaternary Research 38, 1, 129-134.
- **Xiao, J., Porter, S.C., An, Z., Kumai, H., and Yoshikawa, S. (1995)** Grain size of quartz as an indicator of winter monsoon strength on the Loess Plateau of Central China during the last 130,000 yr. Quaternary Research 43, 22-29.
- **Zolitschka, B. and Negendank, J. F. W. (1996)** Sedimentology, dating and palaeoclimatic interpretation of a 76.3 ka record from Lago Grande di Monticchio, southern Italy. Quaternary Science Reviews 15, 101-112.
- **Züllig, H. (1989)** Role of carotenoids in lake sediments for reconstructing trophic history during the late Quaternary. Journal of Paleolimnology 2, 23-40.

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0. TABLE OF CONTENTS APPENDICIES

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A-1 OTHER SOURCES OF INFORMATION

A-1.1 The Ocean Drilling Program

The Ocean Drilling Program (ODP) has developed and extensive set of guidelines related to their large-scale, ship-based drilling operations. Because of the multi-investigator, multi-national character of ODP projects, standardization of methods is a critical consideration. Many of the ODP guidelines are directly adaptable to smaller-scale operations focused on sediments in lakes.
ODP guidelines are published in their Technical Report Series. They are available free of charge from:

Publications Distribution
Ocean Drilling Program
1000 Discovery Drive
College Station, Texas 77845-9547, U.S.A.

The following Technical Report (report numbers, titles, and dates) are especially pertinent to lake drilling operations:
· 3, Shipboard scientist's handbook (1990)
· 6, Organic geochemistry on the JOIDES Resolution - an assay (1986)
· 7, Shipboard organic geochemistry on JOIDES Resolution (1986)
· 8, Handbook for shipboard sedimentologists (1988)
· 9, Deep Sea Drilling Project data file documents (1988)
· 10, A Guide to ODP tools for downhole measurements (1993)
· 12, Handbook for shipboard paleontologists (1989)
· 15, Chemical methods for interstitial water analysis aboard JOIDES Resolution (1991)
· 18, Handbook for shipboard paleomagnetists (1993)

> This information and a variety of other information is available through the:
> ODP World-Wide Web site at: http://www-odp.tamu.edu/

A-1.2 Research Protocols for PALE

The Paleoclimates of Arctic Lakes and Estuaries (PALE) Project has published an extensive set of protocols for its project. The report contains an extensive discussion of coring, sampling, analytical, and dating methods, including detailed recommendations concerning techniques. Although the discussion is focused on high-latitude lakes and estuaries, much of it is applicable to lake sediments in general.

> The report is PAGES Workshop Report 94-1 and is available from the:
> PAGES Core Project Office, Bärenplatz 2, CH-3011 Bern, Switzerland
> Email: pages@ubeclu.unibe.ch.

A-1.3 IMAGES Science and Implementation Plan

The science and implementation plan for IMAGES (International Marine Global Change Study) contains a rationale for studying high-resolution marine records, which parallels the one in this report. The IMAGES document discusses methods related to paleoclimatic records derived from marine sediments and offers a number of recommendations, much of which are pertinent to studies of lakes sediments.

> The report is PAGES Workshop Report 94-3 and is available from the:
> PAGES Core Project Office, Bärenplatz 2, CH-3011 Bern, Switzerland
> Email: pages@ubeclu.unibe.ch.

A-1.4 LRC Core Lab Facility Handbook

This unpublished report discusses the research program, facilities, and methods in use at the Core Laboratory of the Limnological Research Center (LRC) at the Univers-ity of Minnesota. It is a useful guide to an integrated approach by one laboratory to paleoenvironmental reconstructions derived from lake sediments.

> The report is available on the World-Wide Web at:
> http://www.geo.umn.edu/orgs/lrc/lrc.html,
> or from the Limnological Research Center, University of Minnesota, 310 Pillsbury Dr. SE, Minneapolis, MN 55455-0219, USA

A-1.5 Ocean and Land Sample Repository at Lamont-Doherty Earth Observatory

Lamont-Doherty Earth Observatory maintains one of the premier core archives in the world. The Lamont Ocean and Land Sample Repository is seeking to expand its role for non-marine cores. An unpublished document describing the facilities at the Repository and the procedures used for core logging, description, sampling, and archiving is available from:

> Rusty Lotti Bond, Curator
> Deep-Sea Sample Repository
> Lamont-Doherty Earth Observatory of Columbia University
> Palisades, NY 10964 USA
> Email: curator@lamont.ldeo.columbia.edu

A-1.6 PAGES Workshop Report: Global Paleoenvironmental Data

This report, the result of an effort initiated by PAGES but coordinated with all of the Core Projects of the International Geosphere-Biosphere Program, especially the Data and Information Systems (DIS) Project, describes the importance, use, and benefits of paleoclimatic data, ranging from analytical and field results to data needed and generated by climatic modeling. It contains recommendations for data formats, database construction and management, and data archiving.

> The World Data Center-A (WDC-A) for Paleoclimatology in Boulder, Colorado, USA, serves as the data coordination center for PAGES; information and data files can be obtained through the WDC-A World-Wide Web site at: http://www.ncdc.noaa.gov/paleo/paleo.html.
>
> The report is PAGES Workshop Report 95-2 and is available from the:
> PAGES Core Project Office, Bärenplatz 2, CH-3011 Bern, Switzerland
> Email: pages@ubeclu.unibe.ch.

A-1.7 Edited Volumes on Lake Sediments

A number of volumes on various aspects of lake sediments have been compiled over the years, and they serve as useful overviews, guides to methods, and sources of other information. They include:

> **Berglund, B. E.**, (ed.) (1986) Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley and Sons, Chichester.
> **Bradbury, J.P. and Dean, W.E.** (eds.) (1993) Elk Lake, Minnesota: Evidence for Rapid Climate Change in the North-Central United States. Geological Society of America Special Paper 276, Boulder, CO.
> **Haworth, E. Y. and Lund, J. W. G.** (eds.) (1984) Lake Sediments and Environmental History. Leicester University Press.
> **Lerman, A.** (ed.) (1978) Lakes: Chemistry, Geology, Physics. Springer-Verlag, New York.
> **Gray, J. E.** (ed.) (1988) Aspects of Freshwater Paleoecology and Biogeography. Paleogeography, Paleoclimatology, Paleoecology, volume 62.

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APPENDICE A-1.

A-2. INVENTORY OF DRILLING EQUIPMENT FOR RECOVERY OF LONG LACUSTRINE SEQUENCES

Compiled by Dr. S. Leroy
Centre for Palaeoecology, School of Geosciences,
Queen's University of Belfast
Belfast BT7 1NN, Northern Ireland, United Kingdom

A-2.1 Introduction

As an outgrowth of the Workshop, PAGES sent a questionnaire worldwide in order to inventory existing drilling systems capable of obtaining long lake records as recommended in this workshop report. Six drilling and one coring system are described here. For four of them (NEDRA, Eurodrill, Sedidrill, and Usinger), one or more research scientists or scientific laboratories are part of the management structure. FORAKY, CNEA, and BIP are commercial companies, although the former has already drilled for scientific purposes and the latter two are keen to start. These systems all use multiple-entry coring, and most of them use core barrels with liners. They can drill through tens to hundreds of meters of water and through similar thicknesses of sediment.

Some systems that were used to drill well-known sites are not included here. Lake Biwa was drilled by a unique system described by Horie (1987; 1991): a cylindrical drilling pipe engineering method based on the principle of a bottle floating in water. Recent drilling in a Cenozoic lacustrine basin near Fort Yukon, Alaska, by the U.S. Geological Survey used a truck-mounted, self-contained Portadrill 524 rotary core rig (Ager, 1996). We have not systematically surveyed the vast array of commercial drilling equipment.

Several institutions maintain World-Wide Web pages with information about their coring systems and operations. These include:

> Department of Tropical Environment Studies and Geography,
> James Cook University (John Luly; a PVC coring system):
> http://ikarus.jcu.edu.au/TESAG_TESAGers/staff/jlwww/pvc_core/core_pg.htm.
>
> Limnological Research Center, University of Minnesota:
> http://www.geo.umn.edu/orgs/lrc/lrc.html

Multiple-entry coring devices designed to retrieve less than about 20 m of sediment are widely available and are not described here. Examples include the hydraulic push corer at the Limnological Research Center of the University of Minnesota (as much as 20 m; Appendix 1); the Merkt-Streif system (Merkt and Streif, 1970); and the modified Livingstone corer (Livingstone, 1965; Wright, 1967, 1980, 1991; Wright et al., 1965). Under favorable circumstances, these systems can recover substantially more than 20 m.

In addition to the platforms listed below, Philipp Hoelzmann (phoe@fub46.zedat.fu-berlin.de) recommends the use of the Jet-Float system: it is a mobile platform made up of several plastic cubes of

50x50 cm (or 100x100 cm). Set together, they form a platform of about 4x4 m up to x6 m. The stability of the platform varies with its size. It can only be used with no or small waves. The address for the cubes is:

Duwe and Partner, Jet-Float,
Bringhaeuser Strasse 6, Yachthof B1, D-34513 Waldeck-Scheid, Germany
Tel.: +49-5634-1242, fax.: +49-5634-1796.

The approximate price is 110 DM for 50x50 cm cube, and 170 DM for 100x100 cm cube.
The prices quoted in the responses are for 1995. The following abbreviations are used for diameters of various drilling pieces: Ø, diameter; iØ, inner diameter; oØ, outer diameter.

A-2.2 The questionnaire

A. - List of equipment available for coring-drilling continental sections for PAGES' purposes.
1. What is the name of the coring-drilling system?
2. Where is it located?
3. What is the name of the contact person (his/her address including e-mail)?
4. Description of the system: a) system type: rotation, piston, gravity; b) inner, outer diameter of the core, of the casing; c) diameter of the liner, if any, type of liner, transparent or not; d) method of extrusion if necessary; e) length of the core barrels; f) extension rods; g) tripod; h) power supply/ies, push force of the engine; i) winch(es); j) platform size, raft resistance necessary to extract the core out of the sediment; k) need of a crane; l) other.

B. - Transport of equipment
1. What is the total weight of the equipment? Total volume?
2. Is the system portable? How many people? What is the weight of the heaviest piece?
3. How do you usually carry the equipment from the laboratory to the working site? By truck (yours or rented)? By container? How big?
4. How are the cores transported to the laboratory (cooled, container, etc.)?

C. - Past experience
1. Where was the system used? Location name, type of lake, publication.
2. How deep can your system go? Detail the water depth and the sediment penetration.
3. Can your system work on land as well as from a lake surface and from ice?

D. - Potential of the system
1. What, in your opinion, can be achieved with the system in addition to the experience you have until now (water depth, penetration, etc.)?
2. Can you work at high and low temperatures, and altitudes?

E. - General information
1. How many people are needed in total to operate the system? How many people with experience in using the system are necessary?
2. Does the sediment rotate inside the core barrel? Is it possible to orient the cores for palaeomagnetic studies?
3. What would be the cost you would ask to rent the equipment as a service for scientific purposes? What is the real cost of operation?
4. What are the other laboratories equipped in the same way?
5. Any other information you think is important
6. Any other contributor that should be contacted, any other type of equipment to be included.
7. What are according to you the major advantages and disadvantages of your equipment for the drilling-coring of PAGES-type palaeorecords? Technical or other ?

(goes to web) DRILLING SYSTEMS: THE RESPONSES

APENDICE A-2.

A-3. LIST OF PARTICIPANTS

Dr. Thomas Ager
U.S. Geological Survey, MS 919
PO Box 25046,
Federal Center
Denver CO, 80225
USA
Phone: +1-303-236-5728
Email: tager@gdsvr1.cr.usgs.gov

Dr. Daniel Ariztegui
Geologisches Institut
ETH Zentrum
Zurich 8092
SWITZERLAND
Phone: +01-632-3673
Fax: +01-632-1080
Email: daniel@erdw.ethz.ch

Dr. Steven M. Colman
U.S. Geological Survey
384 Woods Hole Rd.
Woods Hole, MA 02543
USA
Phone: +1-508-457-2341
Fax: +1-508-457-2310
Email: scolman@usgs.gov

Prof. John R. Dodson
Dept. of Geography
University of Western Australia
Perth WA, 690
AUSTRALIA
Phone: +61-9-380-269
Fax: +61-9-380-105
Email: dodson@uniwa.edu.au

Mr. Mathieu L. Duvall
INSTAAR
University of Colorado
Campus Box 450
Boulder CO, 80309
USA
Phone: +1-303-492-0246
Fax: +1-303-492-6388
Email: duvall@spot.colorado.edu

Dr. Michele Fratta
European Science Foundation
Strasbourg F-67080
FRANCE
Phone: +33-3-88-76-71-29
Fax: +33-3-88-37-05-32
Email: lesc@esf.c-strasbourg.fr

Dr. Françoise Gasse
Laboratoire D'Hydrologie et de Géochimie Isotopique
Université de Paris Sud
Bâtiment 504
Orsay Cedex 91405
FRANCE
Phone: +33-1-69-41-67-56
Fax: +33-1-64-46-59-38
Email: gasse@geol.u-psud.fr,
or chalie@geophy.geol.u-psud.fr

Dr. Miguel A. González
Carl C:zon Caldenius Foundation
C.C. 289 Sucursal 13 B
Buenos Aires 1413
ARGENTINA
Phone: (54-1) 581-7038
Fax: (54-1) 682-4315
Email: postmaster@funcar.org.ar

Dr. Thomas Goslar
Radiocarbon laboratory
Silesian Technical University
Krzywoustego 2

Mr. Alain Govaerts
Foraky Co.
Belguim
Phone: +322-255-0451

Gliwice 44-100
POLAND
Phone: +48-32-372662
Fax: +48-32-372254
Email:
goslar@zeus.polsl.gliwice.pl

Fax: +322-253-1503

Prof. Henry Hooghiemstra
Department of Palynology,
Hugo de Vries Lab
University of Amsterdam
Kruislaan 318
Amsterdam 1098 SM
THE NETHERLANDS
Phone: +31-20-525-7857
Fax: +31-20-525-7662, or 7715
Email: hooghiemstra@bio.uva.nl

Prof. Shoji Horie
GeoForschungsZentrum
Telegrafenberg A26
Potsdam D-14473
GERMANY
Phone: +49-331-288-1301
Fax: +49-331-288-1302

Prof. Thomas C. Johnson
Large Lakes Observatory
University of Minnesota
Duluth MN, 55812
USA
Phone: +1-218-726-8128
Fax: +1-218-726-6979
Email: tcj@d.umn.edu

Prof. Ramon Julia
Consejo Superior de
Investigaciones Cientificas
Institute of Earth Sciences
Marti i Franquès,
s/n Zona Universitaria
Pedralbes
Barcelona E-08028
SPAIN
Phone: +34-3-490-0552
Fax: +34-3-411-00-12
Email: ramon.julia@u.ija.csic.es

Prof. Kerry Kelts
Limnological Research Center
310 Pillsbury Dr. SE
University of Minnesota
Minneapolis MN, 55455-0219
USA
Phone: +1-612-624-0275
Fax: +1-612-625-3819
Email:
kkelts@maroon.tc.umn.edu

Dr. Suzanne A. G. Leroy
Center for Palaeoecology
Queen's University of Belfast
Belfast BT 7 1NN
NORTH IRELAND
Phone: +44-1232-335 143
or 245-133 ext 3978
Fax: +44-1232-321-280
Email: s.leroy@qub.ac.uk

Prof. Neil MacIntosh
SOILTECH Ltd.
P.O. Box 39075
Bramley, 2018
SOUTH AFRICA
Phone: +2711-887-2700
Fax: +2711-887-5716

Mr. John W. Magee
Division of Archaeology and
Natural History
RSPAS, Australian National
University
Canberra ACT 0200
AUSTRALIA
Phone: +61-6-249-2761
Fax: +61-6-249-4917

Email:
jwmagee@coombs.anu.edu.au

Prof. Vera Markgraf
INSTAAR
University of Colorado
Boulder CO, 80309-0450
USA
Phone: +1-303-492-5117
Fax: +1-303-492-6388
Email:
markgraf@spot.colorado.edu

Dr. Ian MacGregor
Division of Earth Sciences
National Science Foundation
4201 Wilson Blvd
Arlington VA, 22230
USA
Phone: +1-703-306-1553
Fax: +1-703-306-0382
Email: imacgreg@nsf.gov

Dr. Jurgen Mienert
GEOMAR
Wischhofstrasse 1-3
D-2300 Kiel 14, Gebaude
GERMANY
Phone: +49-431-72-02-0
Fax: +49-431-72-53-91

Prof. Jörg F.W. Negendank
Geoforschungs Zentrum Potsdam
Aufgabenbereich 3
Telegrafenberg a26
Potsdam D-14473
GERMANY
Phone: +49-(0) 331-288-1300
Fax: +49-(0) 331-288-1302
Email: neg@gfz-potsdam.de

Prof. Frank Oldfield
PAGES Core Project Office (and U. Liverpool)
Bärenplatz 2
CH 3011 Bern
SWITZERLAND
Phone: +41-31-312-31-33
Fax: +41-31-312-31-68
Email:
oldfield@pageigp.unibe.ch

Prof. Matti Saarnisto
Geological Survey of Finland
Betonimiehunkuja 4
Espoo FIN-02150
FINLAND
Phone: +3580-46-931
Fax: +3580-462-205
Email: matti.saarnisto@gsf.fi

Prof. Liu Tungsheng
Institute of Geology
Chinese Academy of Sciences
PO Box 9825
Beijing 100029
CHINA
Phone: 861-202-7766 ext. 345
Fax: 861-255-8066 / 861-491-9140

Prof. Douglas F. Williams
Baikal Drilling Project
Department of Geological Sciences
University of South Carolina
Columbia SC, 29208
USA
Phone: +1-803-777-7525
Fax: +1-803-777-6304
Email: baikal@epoch.geol.sc.edu

Dr. Herman Zimmerman
Division of Atmospheric Sciences
National Science Foundation
Arlington VA, 22230
USA
Phone: +1-703-306-1527
Fax: +1-703-306-0377

Dr. Bernd Zolitschka
Geologie Universität Trier
Postfach 3825
Trier D-54286
GERMANY
Phone: +49-651-201-4644
Fax: +49-651-201-3915

Email: hzimmerm@nsf.gov Email: zoli@pcmail.uni-trier.de

A-4. LIST OF ACRONYMS

AGCM	Atmospheric General Circulation Model
BAHC	Biospheric Aspects of the Hydrological Cycle (IGBP)
CLIVAR	Climate Variability and Predictability (WCRP)
DIS	Data and Information System (IGBP, HDP)
ENSO	El Niño/Southern Oscillation
EPC	European Paleoclimate and Man Project
EPICA	European Programme for Ice Coring in Antarctica
GAIM	Global Analysis, Interpretation and Modelling (IGBP)
GCTE	Global Change and Terrestrial Ecosystems (IGBP)
GISP 2	Greenland Ice Sheet Project - Two
GRIP	Greenland Icecore Project
AEAI	International Atomic Energy Agency
IAI	Inter - American Institute for Global Change Research
IASC	International Arctic Science Committee
ICDP	International Continental Drilling Program
ICSU	International Council of Scientific Unions
IDEAL	International Decade of East African Lakes
IHDP	International Human Dimensions Programme
IGBP	International Geosphere - Biosphere Project
IMAGES	International Marine Global Change Study
INQUA	International Union for Quaternary Research (ICSU)
ITASE	International Trans - Antarctic Scientific Expedition
LOICZ	Land - Ocean Interactions in the Coastal Zone (IGBP)
NAD	Nansen Arctic Drilling Project
NAFCOM	Northern Africa Regional Committee for START
PAGES	Past Global Changes (IGBP)
PALE	Paleoclimates from Arctic Lakes and Estuaries
PANASH	Paleoclimates of the Northern and Southern Hemispheres
ODP	Ocean Drilling Program
PEP	Pole - Equator - Pole (PAGES transects)
PMIP	Paleoclimate Modelling Intercomparison Project
SCAR	Scientific Committee on Antarctic Research (ICSU)
SCOR	Scientific Committee on Ocean Research (ICSU)
START	System for Analysis, Research & Training (WCRP, IGBP, HDP)
WAIS	West Antarctic Ice Sheet Project
WCRP	World Climate Research Programme
WDC-A	World Data Center - A for Paleoclimatology

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