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Paleolimnological records of climatic change in North America

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Abstract

Lacustrine fossil records provide long time series of data on limnological and climatic conditions; these data are useful for establishing natural patterns of climate variability and for generating testable hypotheses about atmospheric circulation and climate-ecosystem linkages. Shoreline features can indicate past lake-level fluctuations that may reflect changes in moisture balance, but often these records are discontinuous and are evidence of only extreme conditions. The organisms, geochemistry, and sedimentology of lake sediments may provide a more continuous sequence of direct and indirect lake-climate interactions in the past. The most clearly interpretable paleolimnological records of climatic change are those that use several lines of evidence to corroborate a climatic hypothesis and are from sites near an ecotone or in regions of extreme climate. In all cases, hydrologic setting mediates a lake's response to climate and must be considered in interpreting sedimentary sequences.

Discussion of the impact of recent and future climatic changes necessitates a baseline against which the magnitude of observed or predicted changes can be measured. Commonly we look to recent history as a reference point for comparison; however, the landscape of recent decades, or in some cases even centuries, has been altered greatly by human activities. Thus, to determine whether recent or future climatic change is unique or unusual, we need long natural (preanthropogenic) time series against which observed or predicted climatic states and variability can be compared. Paleolimnological archives are a tool for looking at environmental patterns prior to anthropogenic impact and show a range of climatic states far greater than those documented by written records. Former strand lines of pluvial lakes Bonneville and Lahontan in the western U.S., for example, testify to moisture extremes unsurpassed in recent centuries or even millennia. In addition, one can use the paleolimnological record as an independent climatic proxy against which patterns and rates of terrestrial response to climatic change can be compared.

Here, I present a broad overview of paleoclimatic reconstruction in North America from lacustrine records, with a focus on the late Quaternary. The review is limited to climatic inference from paleolimnological records, a term I use in a restrictive sense to refer to records of past lake states (physical, biological, and geochemical), as opposed to records of past stream hydrology (e.g. Ely et al. 1993; Knox 1993) or terrestrial conditions. I summarize paleolimnological tools available for reconstruction of past climate, the capabilities and limitations of these tools,

and some major conceptual issues that arise in studying paleolimnological records.

Paleolimnological records

Climatic influences on lakes are extremely complex and include a diversity of direct and indirect effects. Atmospheric temperature and wind directly affect water temperature and stratification, moisture availability (precipitation minus evaporation, $P - E$) is a primary control on lake level, and temperature and light directly affect organismal growth rates. In turn, stratification patterns and lake levels exert a major influence on lake-water chemistry, which affects growth and reproduction of organisms. In addition, both simple and complex impacts of climate on terrestrial ecosystems and on surface and subsurface hydrology affect a lake's hydrochemistry and thus the structure and function of aquatic communities. Because of the complexity of these influences on the geochemical precipitates and biological fossils in lake sediments, a unique climatic solution from the paleolimnological record may be difficult to obtain. However, this complexity can be addressed through careful site selection and analysis of multiple sedimentary proxies, enabling paleolimnological records to be robust and clearly interpretable archives of past climate and climatic change.

*Lake-level change: Direct linkage of lakes and climate—*Records of changing lake levels are probably the clearest evidence for climatic change. In the western U.S., former shoreline features (strandlines, stromatolites, littoral sediments) document rises and falls in the levels of large lakes that covered vast areas of the Great Basin during the late Pleistocene (Benson et al. 1990). Sensitivity analysis of coupled climatic and hydrologic models can constrain the climatic conditions that drove the tremendous lake-level variations (Hostetler and Benson 1990) and point to potential lake-climate feedback (Hostetler et al. 1994). Former deltas and other sedimentological features of influent streams also can be used to infer fluctuations

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in lake level (Stine 1990). Drowned relict trees rooted in the littoral zone are evidence of relatively recent lake-level excursions and in the eastern Sierra of California suggest extensive drought during medieval times (Stine 1994). In the Laurentian Great Lakes region geomorphic and sedimentologic features of marshes, lagoons, and beach-ridge complexes bordering the Great Lakes reveal lake-level variations during the late Quaternary. Here lake level has been controlled primarily by isostatic uplift and downcutting of outlets (Karrow and Calkin 1985); nonetheless, climatically driven changes of smaller magnitude appear to be superimposed on these large-scale fluctuations (Dalrymple and Carey 1990; Fraser et al. 1990).

Lake-level fluctuations are also recorded in deepwater lake sediments. High-resolution seismic records show sedimentary units (Mullins et al. 1991) that may have unconformities formed by lake-level change. These methods are a promising tool for identifying and quantifying the extent of past lake-level lowering, especially in sediments low in organic matter. The grain-size distribution of sediments is depth-dependent (Sly et al. 1983), and lake-level change can be inferred from changes in sediment grain size, structure, and mineralogy (Wolin 1992). The magnitude of lake-level lowering can be quantified from a transect of cores from shallow into deep water to map the lakeward excursion of coarse littoral sediments and shallow-water macrophytes as water level drops. Application of this technique to a series of lakes on a sandplain in west-central Minnesota suggests that the magnitude of lake-level lowering may be mediated by ground-water hydrology (Digerfeldt et al. 1993).

Factors that drive lake-level change include climate, isostasy, tectonics, and groundwater flow (Almendinger 1993). However, in many cases geologic explanations can be eliminated, and thus shoreline and sedimentological records can be interpreted in terms of either a direct climatic influence on lake level or as a climate-driven shift in hydrology. The major disadvantage of these records is that they are discontinuous and thus provide snapshots at only certain points in the past. For continuous records paleolimnologists must rely on geochemical and biological fossils that may record short-lived, less extreme fluctuations in the limnological environment.

Biological and geochemical indicators of limnological and climatic change in topographically open lake basins— Aquatic organisms respond to parameters directly controlled by climate, such as temperature, light, and water-column turbulence, as well as to variables that are at least one step removed from direct climatic control, such as nutrient and ionic concentration. Most reconstructions of climate-related variables from biological fossils in lake sediments are based on correlation of organisms and either climate (temperature or moisture) or climatically sensitive limnological variables. Because high correlation does not necessitate a causal relationship, the issue of what is really driving changes in species composition may be ambiguous.

In the last decade, fossil Chironomidae have been used

in paleoclimatic studies. Earlier investigations qualitatively inferred cold temperatures in the late glacial from the presence of cold-stenothermous taxa typical of Arctic and alpine regions (Walker and Mathewes 1987). More recently, multivariate statistical techniques have measured the correlation between modern chironomid distribution and surface-water temperature (Walker et al. 1991) and have been used to derive transfer functions for quantitative reconstruction of water temperature from fossil remains (Levesque et al. 1993; Wilson et al. 1993). The extent to which chironomid species distributions are directly related to atmospheric temperature and, consequently, the utility of chironomids as paleoclimatic indicators have been debated in the literature (Hann et al. 1992; Walker et al. 1992). Data are sparse on physiological temperature optima for feeding rates, respiration, and growth of different invertebrate species (Moore et al. 1995), and clearly more studies are needed on proximate impacts of temperature and other climate-related variables. Nonetheless the transfer-function approach assumes only strong linear correlation between organisms and inferred variables, not causality, and this correlation allows statistically rigorous paleoclimatic reconstruction (Birks et al. 1990).

Ostracode distribution is also strongly correlated with climatic parameters and lake hydrochemistry. Ostracodes are limited by water temperature and its seasonal variability and can provide information about seasonal air-temperature variability above lakes shallow enough for water temperature to be thermally coupled to air temperature (Forester 1987). Two large databases of modern autecological information on ostracodes have been compiled for North America (Delorme et al. 1977; Forester and Smith unpubl. data) and form the basis for quantitative reconstruction of air temperature, $P-E$ (Forester et al. 1987, 1989), and solute composition (Smith et al. 1992) from fossil assemblages.

Although temperature has a direct impact on photosynthetic rates in diatoms and other algae, the extent to which species differ in their temperature optima is presently unclear. Physiological characteristics of several species grown in culture suggest no differential temperature effect on diatoms growing under nutrient limitation, although temperature may affect growth differentially under nutrient saturation (van Donk and Kilham 1990). Nonetheless, the distribution of some species is highly correlated with temperature (Stoermer and Ladewski 1976), enabling diatom-based reconstruction of this variable from the fossil record. This approach has been used for paleotemperature reconstruction in boreal and Arctic regions of Canada, using information on modern diatom assemblages in transects of lakes from the boreal forest into tundra (Pienitz et al. 1995). The proximate causes of shifts in diatom communities across this gradient probably relate to reductions in organic carbon concentrations as one moves from forest to tundra (Pienitz and Smol 1993) and differences in ionic concentration driven by weathering rates, both of which are controlled by climate.

In the Arctic, Smol (1988) postulated that temperature may be a primary control on diatom assemblages. He

suggested that in years with cold summers, when all but marginal regions of lakes are ice covered, diatoms from aerophilous and shallow habitats will dominate, whereas in warm years more extensive melting may allow development of a planktonic community. Smol's model has not been tested yet, but paleolimnological studies in the high Arctic show shifts in recent diatom assemblages that may be related to temperature change and anthropogenic effects (Douglas et al. 1994). On the basis of similar reasoning, Arctic diatom abundance may be higher in years with an extended growing season, enabling diatom abundances or biogenic silica concentrations to be used as a paleoclimatic proxy (Williams 1994). In other regions, high proportions of diatom species characteristic of arctic environments have been invoked in stratigraphic studies as proxies for late-glacial conditions (Wolfe and Butler 1994).

Nutrient availability is a dominant control on diatom species composition, and in some cases climate may be inferred from changes in species characteristic of differing trophic states. J. P. Bradbury developed and tested a model for Elk Lake, Minnesota, which postulated that years of extended spring mixing result in long periods of high phosphorus concentrations relative to silica as a result of phosphorus regeneration from the hypolimnion (Bradbury 1988). Thus, he used alternations in species characteristic of differing Si:P ratios as a paleolimnological proxy for the duration of spring mixing (Bradbury and Dean 1993). Because of the many factors that control nutrient concentrations, use of this approach requires explicit knowledge of individual lakes and mechanistic relationships among climate, nutrients, and diatom growth (Kilham et al. 1996).

A number of studies have used changes in the relative abundance of planktonic vs. littoral and benthic diatoms to reconstruct lake-level change (Hickman and White 1989; Schweger and Hickman 1989). In regions where lake level is under strong climatic control, these data may be useful in documenting major climatic shifts, such as transitions between dry glacial and moist interglacial environments (Bradbury 1991a,b); however, in temperate lakes and over time scales where climatic change is less extreme, climatic interpretation from planktonic:benthic ratios (in the absence of corroborative data) is rarely well constrained because of the numerous factors that may affect species abundance in both planktonic and littoral habitats.

Other linkages exist between lake-water chemistry and climate that have not been fully exploited yet for paleoclimatic reconstruction. Recent studies in the European Alps correlate fluctuations in diatom-inferred pH with atmospheric temperature. Psenner and Schmidt (1992) argued that in cooler years high inputs of acidic spring meltwater and lowered in-lake alkalinity generation led to lower pH relative to warmer, drier years. The sensitivity of diatoms to pH has been well documented in studies of lake acidification (Birks et al. 1990), and in poorly buffered lakes where alkalinity can be related directly to climatic change (Anderson and Bowser 1986), diatoms may provide a tool for inferring climate-driven shifts in alkalinity.

In freshwater lakes, reconstruction of climate from sediment geochemistry is largely restricted to analysis of oxygen and carbon isotopes in organic and inorganic carbonates. In open systems, where evaporative losses are a small portion of the water budget, the isotopic composition of authigenic carbonates is primarily a function of the isotopic composition of the lake water itself and lake-water temperature. Thus, long-term variation in the stratigraphy of ^{18}O may reflect either temperature change or a change in the source area of precipitation falling on the lake. In regions where a single moisture source dominates precipitation and on time scales where atmospheric circulation patterns are unlikely to have changed, the isotopic composition of carbonates can be used in a general sense as a paleothermometer. Few isotopic studies from North American freshwater lakes have been published since the pioneering work of Stuiver (1970). Most of the studies are from the Laurentian Great Lakes and show excursions in isotopic values associated with pulses of isotopically light glacial meltwater at the end of the Pleistocene (Colman et al. 1994; Fritz et al. 1975). Although these meltwater pulses reflect climatic change in part, they are strongly controlled by isostatic and hydraulic processes associated with retreat of the Laurentide ice sheet. In recent studies in Minnesota, isotopic analyses of ostracodes from lake sediments were used to examine Holocene changes in groundwater flow and water residence time related to climate (Dean and Stuiver 1993; Schwalb et al. 1995).

Sedimentology can suggest changes in sedimentation caused by climate. In deep-water cores from Lake Superior a decrease in grain size from the early to mid-Holocene is thought to reflect reductions in bottom-current velocity associated with decreased wind intensity, particularly during periods of isothermal mixing (Halfman and Johnson 1984). Wind intensity and direction also affect the depth of wave scour and may prevent sediment accumulation in shallow areas (Johnson 1980a,b). Similarly, depositional hiatuses in sediment cores may result from changes in sediment focusing or deposition related to wind (Thayer et al. 1983).

Record of climatic change in topographically closed (saline) lakes—Topographically closed lakes can be sensitive recorders of climatic change because the balance between precipitation and evaporation affects lake level, which in turn alters the concentration of dissolved salts. In most cases climate can be reconstructed with fewer uncertainties from closed-basin lakes compared with open freshwater systems because of the relatively simplified set of linkages governing salinity change.

Diatom distribution is strongly correlated with salinity and with brine type (Blinn 1993; Cumming and Smol 1993; Fritz et al. 1993; Wilson et al. 1994). Shifts in species of differing salinity tolerance have been used for qualitative climate reconstruction in the arid western (Blinn et al. 1994; Bradbury 1988, 1991a,b) and north-central U.S. (Radle et al. 1989). Calibration data sets for quantitative salinity inference have been developed for the northern Great Plains (Fritz 1990) and British Columbia (Cumming and Smol 1993; Wilson et al. 1994).

and applied to climate reconstruction at both centennial and decadal time scales (Fritz et al. 1991, 1994).

Both chironomid and chrysophyte distributions are correlated with salinity, although both groups suffer truncation at high ends of the gradient. Chrysophyte remains (cysts and scales) are restricted typically to fresh and oligosaline water (salinity $<5 \text{ g liter}^{-1}$) (Cumming et al. 1993), but within this range distribution of cyst morphotypes is strongly correlated with conductivity (Zeeb and Smol 1995). Chironomids span a broader salinity range, but a calibration data set from British Columbia (Walker et al. 1995) suggests that only one taxon survives at salinities $>10 \text{ g liter}^{-1}$, so inference equations are insensitive above this point.

Ostracode distribution in saline lakes is correlated with both ionic concentration and composition (Smith 1993; Forester 1983, 1986), with different species characteristic of waters enriched in calcium vs. carbonate (Forester 1987). In closed lakes ionic composition varies in a predictable fashion depending on initial conditions (controlled by geologic setting and hydrology) and the degree of evaporative concentration (Eugster and Jones 1969), and thus the reconstruction of solute evolution from ostracodes can be used for qualitative (Forester 1987) or quantitative (Smith et al. 1992) climatic inference.

Trace elements, such as Mg and Sr, are incorporated into the calcite lattice of ostracode shells in proportion to their relative abundance in the lake water in which the ostracode lived. Thus, the chemistry of the lake water in which the ostracode grew can be reconstructed from ostracode-shell chemistry (Chivas et al. 1986; Engstrom and Nelson 1991). Both Mg and Sr concentrations are related to lake-water salinity and thus to climate; usually, Mg concentrations increase with increasing salinity, whereas the relationship between Sr concentration and salinity depends on the solid mineral phase (e.g. calcite, aragonite) that dominates the system. These relationships between shell chemistry and solute concentration have been used for paleohydrologic reconstructions in the northern Great Plains (Haskell et al. 1996).

In closed-basin lakes the isotopic composition of biogenic and inorganic carbonates reflects not only lakewater composition and temperature, but also strong evaporative concentration, which preferentially evaporates the lighter H_2^{16}O . Although the relative contributions of each of these can be difficult to unravel from an ^{18}O profile alone, isotopic data in combination with other proxies can disentangle evaporative effects from the influences of changes in temperature and (or) atmospheric moisture sources (Benson et al. 1991; Van Stempvoort et al. 1993). In deep lakes, temperature effects on isotopic fractionation can be minimized by analysis of carbonates from beneath the thermocline (e.g. using deep-water ostracodes). Although carbon isotopes typically reflect changes in production or the relative contributions of terrestrial vs. lacustrine sources of organic carbon, analysis of oxygen and carbon isotopes together can be used to assess hydrologic variability. In a closed-basin oxygen and carbon profiles show inverse covariance, whereas open systems show direct covariance (Valero Garces 1996). Although mechanisms for these behaviors are unclear at

present, paired oxygen and carbon isotopic profiles may suggest switches between open- and closed-basin hydrology.

Discrepancies among organismal proxy records may reflect differences in the timing of life-history events, but unfortunately autecological information is limited for most saline-lake organisms. The timing of blooms of common diatom taxa is not known for most systems nor the season when many ostracode species molt and regrow their shells. Diatoms, for example, may respond primarily to spring salinity, whereas ostracodes may reflect salinity later in the growing season. These life-history data hold a wealth of potential paleoclimatic information on seasonality that cannot be exploited yet.

In fluctuating environments, such as in arid-semiarid regions, the composition and texture of sedimentary facies can indicate changes in lake level, basin slope, or detrital influx (Last 1989, 1990; Spencer et al. 1984; Valero Garces and Kelts 1995; Vance et al. 1992). Sedimentology can identify pedogenic zones formed during dry or extremely low water conditions (Teller and Last 1982) or intervals rich in detrital quartz associated with episodes of stream discharge (Allen and Anderson 1993). Mineralogical and geochemical facies analysis can further elucidate paleohydrological changes based on identification of soluble and sparingly soluble salts. Precipitation of endogenic minerals from solution follows predictable patterns based on ionic concentration, composition, and temperature (Eugster and Hardie 1978). For example, in calcite-dominated systems progressive evaporative concentration will produce a sequence from low-Mg calcite to high-Mg calcite to aragonite to dolomite to magnesite (Müller et al. 1972), although detrital or diagenetic carbonates can complicate sedimentary interpretation. Within a single carbonate unit lake-water Mg:Ca can be reconstructed from Mg content (Last and Sauchyn 1993; Teller and Last 1981), with progressive Mg enrichment with increasing salinity. With additional concentration, several evolutionary pathways are possible, depending on initial conditions. In waters enriched with bicarbonate relative to Ca and Mg, alkaline earths are rapidly removed by evaporative concentration to yield brines dominated by sodium carbonates. By contrast, alkaline earths are enriched in systems in which the molar ratio of bicarbonate is low relative to Ca and Mg, producing a Ca-Na- SO_4 -Cl brine. Thus in these more concentrated brines, changing salinity can be inferred from mineral precipitates, such as gypsum or mirabilite (Last 1990; Last and Slezak 1988).

Climatic response and lake hydrology—Lacustrine response to climatic change is mediated by hydrologic setting, and interpretation of sedimentary records in climatic terms must include consideration of hydrology. The relative importance of factors in a hydrologic mass balance governs the magnitude and rate of lacustrine response. Thus, topographically closed lakes respond to changes in the balance of precipitation minus evaporation more rapidly than open systems. In closed basins the relative importance of groundwater vs. evaporative losses governs the magnitude and rate of salinity response to change in

moisture availability: salinity change may be much larger where evaporation dominates hydrologic export than in a system dominated by groundwater seepage, although the former may be slower to reach some steady state (Sanford and Wood 1991). Similarly, coupling between lakes and climate may be damped in a lake with strong riverine or surface-water inputs, in comparison to a lake where inputs are primarily from groundwater. Moreover, the hydrologic mass balance is not static, so river diversion or inflow unrelated or indirectly related to climate may alter lake-water salinity (Bradbury et al. 1989) as can shifts in groundwater source (Smith 1991). Even where change in lake-water hydrochemistry is driven by climate, the relationship may not be simple or direct, and the response may show lags or hysteretic behavior, such that, for example, salinity for a given lake stage may be higher during falling lake levels than when a lake refills (Fritz 1990). Lakes in which water level falls below an outlet threshold may show a rapid salinity change that results from the transition from an open to closed basin. In these situations the rapidity of salinity change may reflect crossing of a limnological threshold under a gradually changing climate rather than a rapid climatic shift (Kennedy 1994). Salinity also responds to the rapidity of lake-level change, and water-level fluctuations may have a more dramatic effect on salinity at low lake stages because of the smaller volume.

The relative position of a lake in the regional groundwater flow regime also affects lake response to climate. Hydrologic modeling suggests that a lake close to the river that acts as the discharge point will be less sensitive to changes in effective moisture than a lake farther from the river (Almendinger 1990); this pattern has been confirmed by stratigraphic studies (Digerfeldt et al. 1993). Thus, one must be cautious in inferring the magnitude and rate of climatic change from the stratigraphy of a single lake, for each basin may respond to some extent in an individual fashion. These climatic and hydrologic linkages can be predicted by comparing stratigraphic records in a series of lakes (Digerfeldt et al. 1993), by empirical calibration of modern salinity or lake-level behavior to meteorological records (Laird et al. 1996), or, ideally, by groundwater modeling of each basin (Donovan 1994a,b).

Conclusions

The clearest paleolimnological records of climatic change are direct records of lake-level fluctuations, particularly from shoreline evidence or systems where multiple proxies have been used to corroborate a climatic hypothesis (Bradbury and Dean 1993). In general, systems most sensitive to climatic change are those in which a small change in climatic forcing causes a large change in the limnological environment, including lakes in extreme habitats, such as the high Arctic, or lakes near an ecotone or climatic boundary, such as those near treeline or the prairie-forest border. Extremely large lakes may record climatic extremes, whereas small shallow systems

may record strong seasonal variability rather than long-term climatic trends. In general, lakes most likely to clearly record climatic signals are of moderate size and catchment and are hydrologically simple with no surficial outlet and with inputs dominated by groundwater. Climatic interpretation from the stratigraphy of other systems, including large lakes or temperate lakes distant from a major climatic boundary, usually requires detailed and specific data on the relationships among climate, limnology, and the proxy record of concern.

Significant insights about climatic patterns and processes have emerged from paleolimnological reconstructions. Clearly, the range of possible climatic states is great (Bradbury 1991a,b), and even on time scales of hundreds of years, the historic record does not adequately represent the range of possible behaviors (Fritz et al. 1994; Stine 1994). The broad patterns of change as reconstructed from the paleolimnological record have been used to pose hypotheses about changes in atmospheric circulation patterns and interactions between lakes and climate, which can be explored with climatic-hydrologic models (Hostetler and Benson 1990; Hostetler et al. 1994). The paleolimnological record can also be used to pose questions about patterns and mechanisms of limnological response to climate (Kilham et al. 1996) that can be tested with modern studies of geochemical dynamics or organismal physiology and autecology. I suggest that the most important function of the paleolimnological record is that it generates data on long-term patterns of diverse components of the environmental system, at a diversity of spatial and temporal scales, which subsequently can be used to pose questions about climatic, terrestrial, or limnological processes.

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