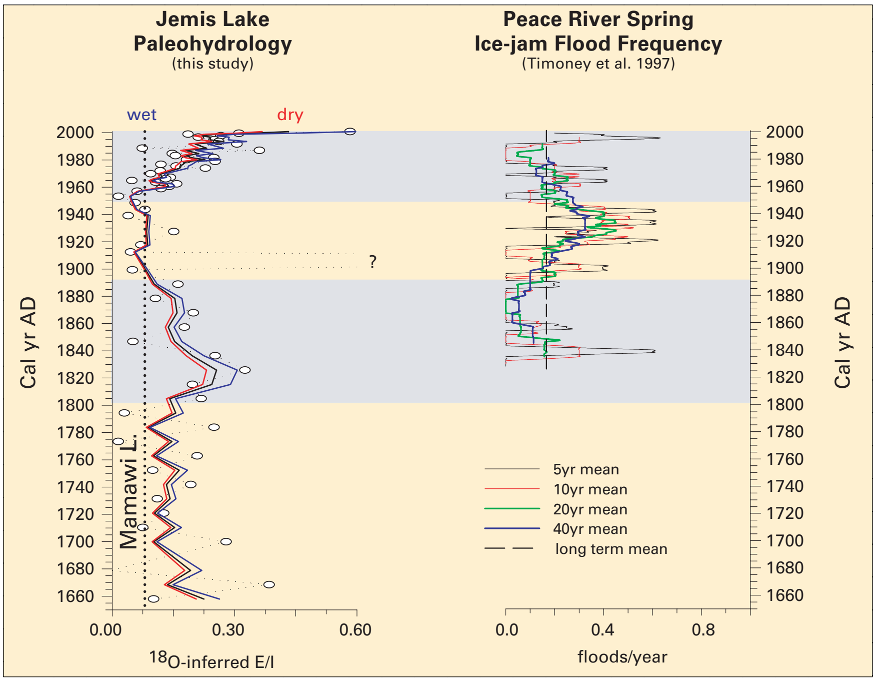

Fig. 2: Comparison of isotope-inferred water balance (expressed as evaporation/inflow ratio, E/I) of Jemis Lake with Peace River ice-jam flood frequency reconstructed from observational and anecdotal evidence by Timoney et al. (1997). Two multi-decadal periods of relatively dry conditions (high average E/I, marked by shaded zones) in Jemis Lake and persistently low ice-jam flood frequency have apparently occurred within the past 175 years, with the current dry phase beginning in the mid-1900s. [Note: This first-order estimation of paleo E/I ratios for Jemis Lake is based on variations in measured $\delta^{18}O$ of aquatic cellulose, assuming "Craig-type" evaporative enrichment of lake waters fed by source waters of constant isotopic composition (e.g., see Gibson, 2001, Wolfe et al., 2001a, b). The modelled values are smoothed by a three-point running mean, and assume an ice-free season relative humidity of 55 ± 10% (black line bracketed by red and blue). The modern E/I ratio for nearby Mamawi Lake (vertical dashed line) provides a reasonable lower limit, since non-flood intervals should be marked by disconnection from this river-fed lake.]

the Athabasca River that recharged the lake with isotopically-depleted river water.

Insight gained from such observations is key to the task of reconstructing the paleohydrology of the PAD over various time periods, which is necessary to provide the context for assessing ongoing change and evolution of the system. Preliminary results from stratigraphic analysis of a short sediment core from Jemis Lake, for example, suggests that changing water balance in this lake, as inferred from aquatic cellulose $\delta^{18}O$, may provide a rough proxy for ice-jam flood frequency on the Peace River, which appears to have fluctuated widely over the past several centuries (Fig. 2). Fuller integration of other multiproxy evidence is certain to refine and sharpen this isotopic tool appreciably (e.g., see Wolfe et al., 2002), as we delve deeper into the paleo-history of the PAD, as well as in extended studies planned over the coming years in the Slave and Mackenzie deltas, downstream.

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Lacustrine Oxygen Isotopic Records from Temperate Marl Lakes

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Sediments from small, temperate, carbonate lakes can provide excellent archives for Late Glacial and Holocene paleo-environmental investigations. The rapid reaction of the local hydrological system to environmental change, coupled with relatively high sediment accumulation rates, facilitate high-resolution stratigraphic studies that can employ a wide range of lithological, chemical and biological proxies. Stable isotopic data can be collected relatively easily from authigenic carbonates, which precipitate in the water column, and from the calcareous skeletons of macro and micro-fossils. Ostracods that inhabit different lacustrine settings and which calcify at different times of the year potentially enable seasonal and depth variations to be determined. Carbonate oxygen isotopic data is particularly useful in that it can provide a record that can be linked to changes in temperature and meteoric precipitation on a scale that can be directly correlated with ice-core records. Because water residence times are short these isotopic records also can be used as a proxy for 'instantaneous' climate forcing – enabling the identification of lag effects and non-linear changes in other proxies which are controlled by processes acting within the lake catchment.

Sediments from several small hard-water lakes are the focus of current investigations funded by the Natural Environment Research Council. The sediment records are being calibrated by the investigation of carbonate precipitation and isotopic variation in the modern lakes (Fig. 1) and a multiproxy investigation in-

Fig 1: Photographs of Hawes Water, NW England. Carbonate precipitation is mediated by photosynthesis. Site monitoring enables determination of the season of carbonate precipitation and the local relationship between temperature, water and carbonate compositions.

volving detailed study of pollen, chironomids and sediment properties.

Local Calibration and Verification of Oxygen Isotopic Records

Figure 2 illustrates the factors that can influence the oxygen isotopic composition of a carbonate precipitated in freshwater. If a carbonate precipitates in equilibrium with its environment its oxygen isotopic composition depends primarily on the ambient temperature and the isotopic composition of the local water. For fossil sedimentary carbonates, if either water compositions or temperature of precipitation is known or can be estimated, equilibrium equations enable calculation of the 'unknown' (temperature or water composition). In the absence of 'known' values; relative changes in temperature or the isotopic composition of the water can be calculated.

An understanding of the conditions under which carbonate precipitation takes place in the modern lake is thus critical to understanding the sediment record. Equilibrium precipitation cannot be assumed for either biogenic or authigenic precipitates in natural environments: local (even within-organism) changes in pH, speciation and supersaturation may influence isotopic fractionation. Studies of the isotopic systematics of inorganic and biogenic carbonate precipitation in modern lakes can be used to provide a local verification of the sediment record by constraining the data from sediment cores. In the case of Hawes Water, for example, extensive monitoring of the lake chemistry, temperature, saturation state and carbonate precipitates has been carried out over a two-year period. The carbonate precipitates in the summer months and in the surface waters of the lake. The sedimentary record will therefore preferentially record changes in summer/surface conditions. Carbonate saturation states in the modern lake are never high enough for direct inorganic precipitation. The precipitation of carbonate is mediated by the photosynthesis of both macrophytes and algae and most of the micrite forms on plant and algal substrates (Fig. 1). By carefully taking sediment samples and monitoring water compositions it has been possible to determine that the carbonate values approach those of inorganic equilibrium. However there appears to be a systematic offset, and a slightly reduced temperature gradient, which may be associated with kinetic effects (Fig. 3). We have thus successfully determined a local temperature/water composition relationship that can be used in the interpretation of the sediment records.

The PAGES-ISOMAP initiative highlights the climatic importance of mapping the isotopic composition of meteoric water as a variable that can be directly modelled by global climate models. Lake water compositions are likely to dominantly reflect the composition of local rainfall but local effects – including evaporation (in the recharge zone and from the lake itself), water/rock interaction and differential mixing or separation of seasonal rain may influence the composition of a particular lake. It is important to understand possible temporal variation in the lake isotopic compositions (Fig 2). Unlike closed lakes at low latitudes, evaporation effects are likely to be minimal in temperate conditions. However, in lakes that become thermally stratified, like Hawes Water, the isotopic composition of the water becomes stratified as summer rainfall (with markedly higher $\delta^{18}O$ than the annual mean) is preferentially kept in the surface waters during the season of carbonate precipitation. Such effects lead to an enrichment of ~1‰ in the surface waters.

Late Glacial Data – Climatic Significance

The Late Glacial oxygen isotope record from Hawes Water (Fig. 4) illustrates the sensitivity of temperate marl lakes to environmental change. The $\delta^{18}O$ record clearly distinguish-

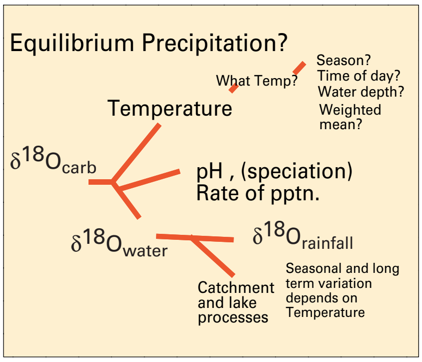

Fig. 2: Factors that can influence the oxygen isotopic composition of lacustrine carbonates.

es the cold Younger Dryas stadial from the preceding and much warmer Late Glacial interstadial. The structure of the Younger Dryas isotopic excursion suggests rapid cooling followed by an early phase of warming that long preceded the major warming that ended the stadial. This structure is also recognised in the GRIP ice-core record. The longer-term pattern also records four short-lived cold events in the interstadial (A-D on Fig. 4). The pattern has close parallels with those from the high-resolution chironomid temperature record from southern Scotland (Whitrig Bog; see Brooks and Birks, 2000), the ostracod isotopic re-

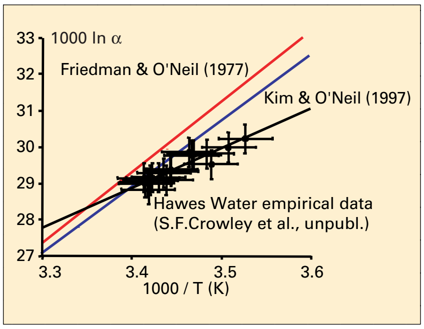

Fig. 3: Locally determined isotopic fractionation for carbonate precipitates at Hawes Water compared to published equilibrium relationships.

cord from Ammersee in central Europe (von Grafenstein et al., 1999), and the GRIP ice-core record (Fig. 4). Interestingly, although the overall pattern of change is similar there are some apparent discrepancies between the relative timing of the interstadial optimum and the relative magnitude of the interstadial events. These may be significant in terms of the detailed climate dynamics of the north Atlantic region.

A discussion of the Hawes Water results in terms of changes in temperature and meteoric water compositions will be published shortly (Marshall et al., in press). Simple calculations imply significant fluctuations in both temperature and meteoric water compositions during the interstadial and Younger Dryas. Significantly, changes in temperature calculated from the isotopic record are similar to those derived for the UK from Coleopterid records and the marine Atlantic diatom record. However they are significantly greater than those derived from the Chironomid palaeothermometer at Whitrig Bog. There is clearly a need to resolve this apparent discrepancy between the proxies if we are to develop a quantitative understanding of climate change. Ideally, chironomid and isotopic data are needed from the same archive and at the same resolution. Most chironomid studies and the entire calibration training set used to develop the temperature inference model are based on data from soft-water, relatively acidic lakes. As a first step to resolving the problem we are currently trying to obtain a high-resolution chironomid record for the Hawes water site.

Many indicators of climate change, such as pollen or changes in detrital sediment input, take time to react to changes in local climate. Alternatively, there may be no reaction to climate change at all until a critical threshold has been reached. The isotopic composition of carbonate precipitated in small lake systems with relatively short water residence times will, however, react rapidly to changes in climate that affect the local temperature or the isotopic composition of the water. The oxygen isotopic record may thus provide a proxy that records a more or less instantaneous response to climate

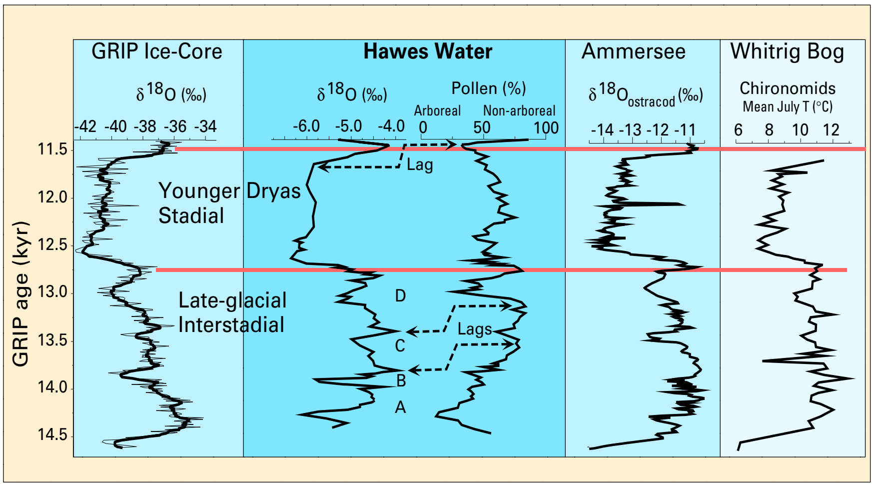

Fig. 4: Late Glacial isotopic and floral data from Hawes Water NW England compared to the GRIP ice-core $\delta^{18}O$ record, the Ammersee ostracod record and the Whitrig Bog chironomid temperature reconstruction.

forcing. By comparing the isotopic record of environmental change at Hawes water with a detailed record of changes in the catchment, using pollen and magnetic analysis, it has been possible to identify differences in response times for different elements of the flora as well as for input of detritus (Jones et al., in press). Figure 4 shows an example of the lag effects associated with colonisation of the Hawes Water catchment following the end of the Devensian glaciation.

Conclusions

Sediments deposited in small, hard-water lakes can produce high-resolution isotopic records of environmental change that respond directly and immediately to external climate forcing. Some of the problems with the quantitative interpretation of the oxygen isotopic records can be minimised by site-specific calibration exercises to ascertain whether carbonate froms in equilibrium and to determine the current conditions of carbonate formation. Given independent high-resolution monitors of temperature change, like those from chironomid or coleopteran transfer functions, it will be possible to use the oxygen isotopic records as a direct measure of changes in the isotopic composition of precipitation. These records will provide crucial data for evaluating and refining global climate models.

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