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PAGES news

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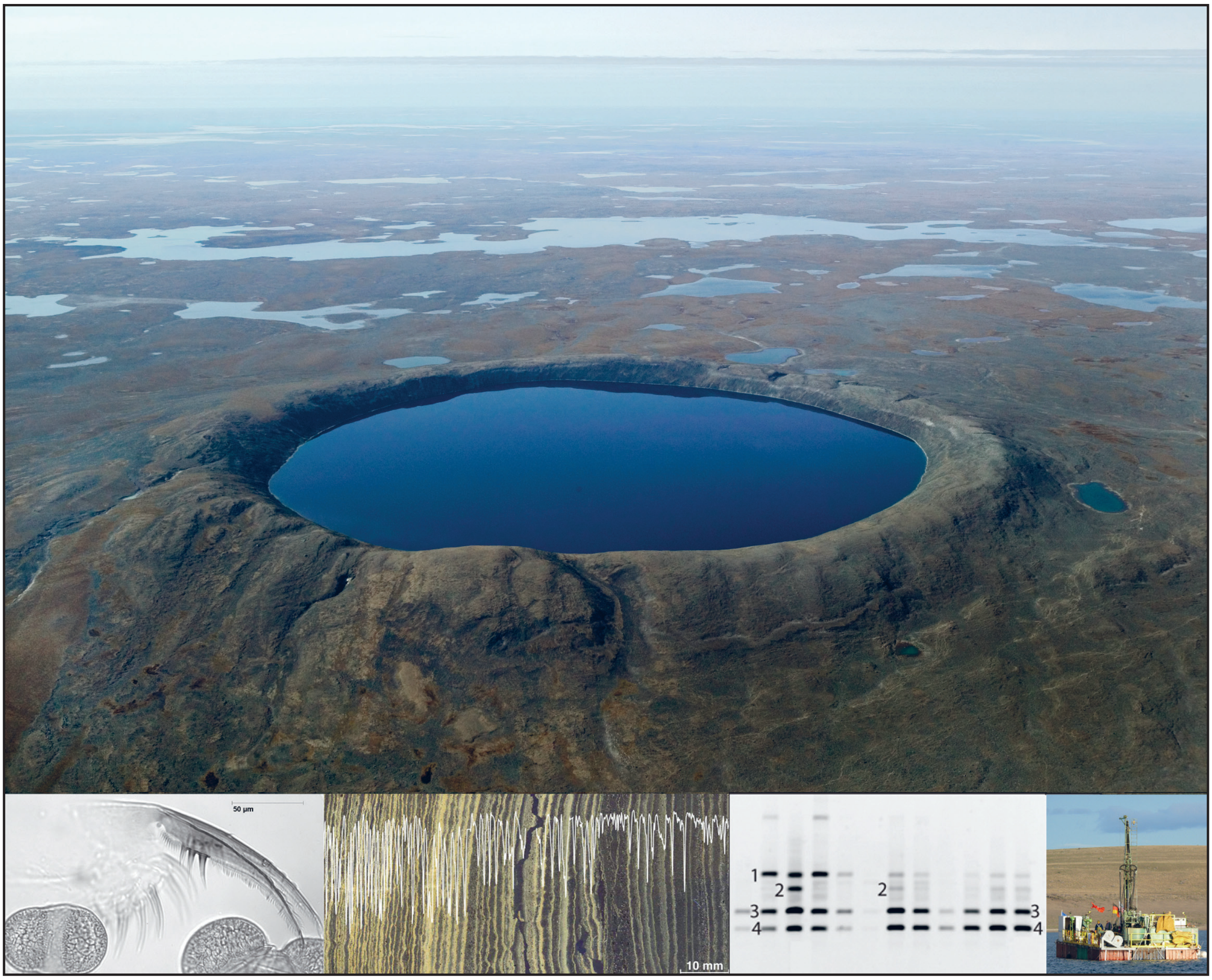
Advances in Paleolimnology

Editors:

Reinhard Pienitz, André Lotter, Louise Newman and Thorsten Kiefer



The historical records contained in lake sediments provide insights into the effects and mechanisms of past climatic and environmental change. This issue of PAGES news *highlights methodological advances in the field of paleolimnology, including proxy reconstructions, DNA analysis and chronology, among others (Photo credits on back cover).*

Inside PAGES

YSM & OSM epilog

PAGES 1st Young Scientists Meeting and 3rd Open Science Meeting were held in July in Corvallis, Oregon, USA (see p. 131-134 this issue). There was a great deal of interaction and networking, and we would like to thank everyone who participated. We received very positive feedback for both meetings and a lot of very useful input on PAGES science activities and future plans. An online poster exhibition has been set up for both meetings and videos of the entire OSM program can be viewed online (http://www.pages-osm.org/osm/videos.html). The videos are available to order gratis in DVD form from PAGES online Product Database (http://www.pages-igbp.org/products/). The inaugural meeting of the PAGES Last 2 Millennia Theme, including representatives from each of the current Working Groups—Africa, Antarctic, Arctic, Australasia, Asia Europe, North and South America—was also held in Corvallis (see p. 130 this issue).

PAGES will hold its next YSM and OSM in 2013. The location is still to be determined. Details will be posted online (http://www.pages-osm.org/) as they become available.

SSC and EXCOM meetings

PAGES Scientific Steering Committee (SSC) and Executive Committee (EXCOM) met in Troutdale, Oregon after the OSM. Discussion items included general business, budgets for the next financial year and the upcoming grant for funding of the PAGES project for 2010-2013, which is due to the Swiss and US National Science Foundations at this end of this year. Minutes from the meetings will soon be available online (http://www.pages-igbp.org/people/sscmembers/meetingminutes.html). SSC members also elected new SSC members for 2010. The new members will be announced in the next issue. In addition, the SSC and EXCOM evaluated proposals for new PAGES Working Groups and applications for workshop funding (see below).

New Working Groups

The SSC and EXCOM approved two new proposals for PAGES Working Groups, one on Varves (under Cross-Cutting Theme 1: Chronology) and another on the Marine Nitrogen Cycle (under the "Paleoperspectives on Ocean Biogeochemistry" Theme of PAGES Focus 3: Global Earth-System Dynamics). To get involved, contact Pierre Francus (pfrancus@ete.inrs.ca) and Markus Kienast (markus.kienast@dal.ca), respectively. Information on these and other Working Groups, or on how to propose a new Working Group within PAGES can be found online (http://www.pages-igbp.org/science/workinggroups.html).

Workshop Support

Three proposals to the Open Call for Workshop Support in May were awarded financial support. The newly formed Varve WG was allocated funding for its first workshop, planned for the end of 2009/beginning of 2010 in Estonia. The two other supported meetings, both INQUA activities, were a West African Quaternary workshop on paleoclimatic sea level changes and anthropogenic responses (Nigeria, 26-30 October 2009), and a workshop on tephrochronology, volcanism and human activity (Japan, 10-17 May 2010). Details are in PAGES online calendar of paleo-events (http://www.pages-igbp.org/calendar/). The next Open Call deadline is Sunday, 15 November 2009. Application guidelines can be found online (http://www.pages-igbp.org/resources/support/guidelines.html).

Hot off the Press

PAGES new *Science Plan and Implementation Strategy*, the third in PAGES 18-year history, was recently published. It aims to galvanize the paleocommunity towards answering the key questions of the coming decade. These questions are directed at developing a better understanding of climate-environment sensitivity, regional variability, global system behavior and human interaction with climate and environment. It is available in digital form and hardcopy. Another strategic document that is now available for download is the revised Vision Document of the PAGES/CLIVAR Intersection Panel that outlines the framework of topics to be tackled by the Panel in the coming years. Other recent PAGES publications are the *Palaeogeography, Palaeoclimatology, Palaeoecology* special issue (281:3-4, 175-376) on "Long-term multi-proxy climate reconstructions and dynamics in South America (LOTRED-SA): State of the art and perspectives", (conference proceedings from the LOTRED-SA workshop held in October 2006 in Argentina), and a paper in *Nature Geoscience* (doi:10.1038/ngeo660), "Interglacial diversity", resulting from the first PIGS (Past Interglacials) Working Group meeting held in October 2008 in France. Further details and/or downloads of above products are available through PAGES online Product Database at http://www.pages-igbp.org/products/

Next issue of PAGES News

The first issue for 2010 will contain a special section on peatland paleoscience, guest edited by Stephen Jackson and Dan Charman. The deadline for contributions to this special section as well as to the open section, unrelated to the peatland topic, is 11 January 2010. Guidelines for contributions can be found online (http://www.pages-igbp.org/products/newsletters/instructions.html).

Eulogy: John "Jack" Eddy

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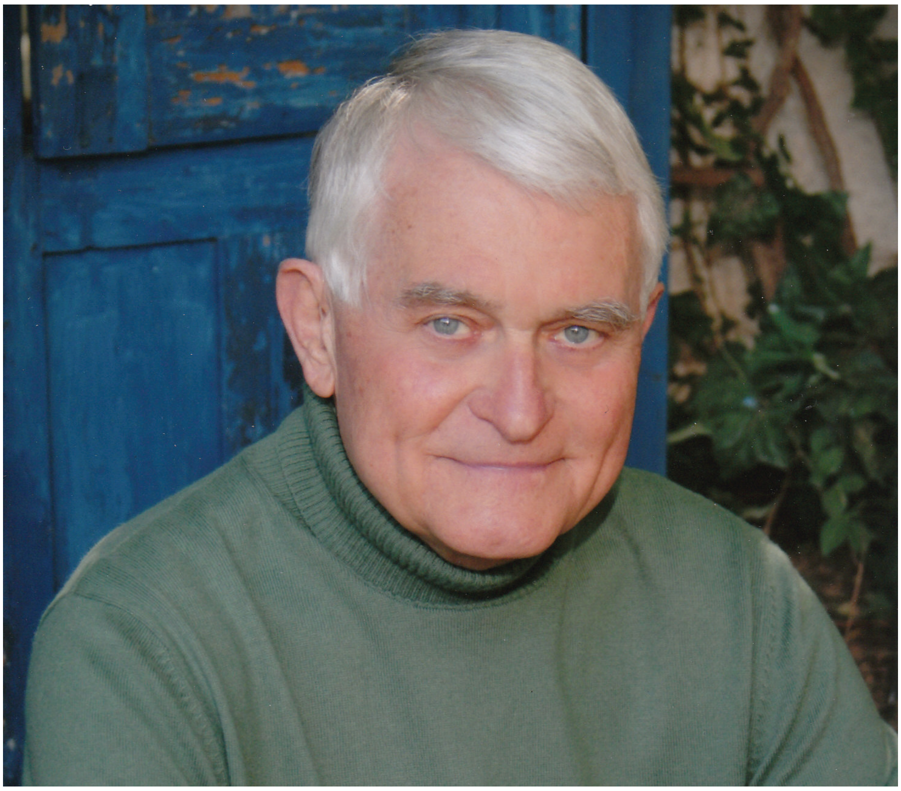
Sadly, one of the guiding lights and strongest supporters of PAGES passed away on 10 June 2009. John A. Eddy, known to all his friends as Jack, played a key role in promoting the concept of interdisciplinary research and the important perspective that studies of past climate changes could bring to Earth System science.

As Director of the Office of Interdisciplinary Earth Studies within the University Corporation for Atmospheric Research (UCAR) in Boulder, Colorado, Jack became an influential and eloquent spokesman for the kinds of interdisciplinary research that we take for granted nowadays. But in the 1980s, the concept was a hard sell; breaking down the walls that separated the traditional disciplines was difficult. Jack never wavered in his ardent belief that a more holistic view of the Earth was essential, and he used his considerable persuasive talents and his reputation as an eminent astrophysicist to promote this agenda. One of the most important steps in this process was the "Global Change Institute" that he organized in the summer of 1989, in Snowmass, Colorado. This brought together many of the leaders in paleoclimatology from around the world to work together for 2 weeks, challenging each other's ideas and developing the plans that later became the foundation of the PAGES scientific strategy (Bradley and Eddy, 1991). At the same time, the Science Advisory Council for IGBP committed to, "*a major new international research project dealing with ... a coordinated effort to recover information from natural archives that will illuminate connections between atmospheric composition, global temperature, ice extent, solar history, and the distribution of land and oceanic organisms*".

This meshed perfectly with Jack's vision of what was needed, and in 1991 the first meeting of the PAGES Scientific Steering Committee was held in Mainz. I fondly remember Jack leading a critical discussion—what should the new project be called? There was already a potential acronym—"PaGloCha" (Past Global Changes) but this hardly seemed to have the same catchiness and imagery that "PAGES" had. After all, wasn't the plan to use natural archives to look back in time, as one might flip back through the pages of a book? Jack was his usual persuasive self, and the new name was readily adopted. He then played a critical role in obtaining a commitment from the U.S. National Science Foundation to team up with the Swiss Science Foundation and co-fund a coordination office in Bern.



"Jack" Eddy, photographed by Barbara Eddy

The PAGES community has greatly benefited over the years from Jack's relentless and enthusiastic support for the project in its formative years. These are simple facts that document his role. But those who knew Jack will remember him first and foremost as one of the warmest and most sincere individuals you could ever hope to meet.

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PAGES Calendar 2010

15 - 19 Feb 2010 - Bariloche, Argentina
VI Southern Connection Congress - Gondwana reunited: A southern perspective for a changing world
http://www.sccongress2010.com.ar/

10 - 17 May 2010 - Kyushu Island, Japan
International field conference and workshop on tephrochronology, volcanism and human activity
http://www.ris.ac.jp/intav-jp/

10 - 13 May 2010 - Edinburgh, UK
AIMES Open Science Conference "Earth system science: Climate, global change and people"
http://www.pages-igbp.org/calendar/

29 Aug - 3 Sep 2010 - California, USA
10th International Conference on Paleoceanography
http://icp10.ucsd.edu/

13 - 15 Sep 2010 - Shanghai, China
2nd PAGES Global Monsoon Symposium
http://www.pages-igbp.org/calendar/

Editorial: Advances in Paleolimnology

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Lakes are excellent "sentinels of change" (Williamson et al., 2009) because they can provide insight into the effects and mechanisms of climate change. With the historical record offered in their sediments, they also provide natural archives for past environmental change. In many cases, the study of lake sediments (i.e., paleolimnology), and specifically the biotic and abiotic components that integrate information from the water column, catchment area, and atmosphere, can help assess baseline conditions for different physical, chemical, and biological systems (e.g., climate, nutrients, ecosystem functioning), as well as the impacts of and recovery times after disturbances of ecosystems.

Abrupt climate change has become a key issue in paleoclimate research. Understanding the processes and dynamics of rapid and high-amplitude climate shifts (e.g. ENSO, PDO, NAO/AO, Heinrich and D/O events, Younger Dryas) is crucial for a better assessment of the probability of such changes in the future, which bear risks for landscapes, ecosystems, and organisms of all sorts, including humans. "Reliable risk assessment should not exclusively be based on computer model simulations but also on accurate observational and high-resolution paleoclimate data" (S. Rahmstorf, EGU meeting Vienna, 20 April 2009). Such data, needed to refine climate models, can only be generated using state-of-the-art, high-performance analytical techniques.

Paleolimnological approaches can provide robust reconstructions of climate variability and of the sensitivity of lacustrine ecosystems to such changes (e.g., Battarbee et al., 2004; Pienitz et al., 2004; Smol, 2008). Lakes can also yield insights on the hydrological cycle and provide long records where other archives cannot (e.g., trees and ice cores). Many paleolimnological methods are now standardized (e.g., Last and Smol, 2001a; b; Smol et al., 2001a; b). However, relatively little progress has been achieved in the area of developing proxy records that provide sufficient resolution to resolve decadal- to century-scale variability over several millennia, and to understand and refine empirical climate-proxy relationships. Like other fields of environmental science, the paleolimnological community must face these challenges.

After an initial phase of predominantly descriptive studies, the paleolimnology community has been developing and improving the numerical foundations for quantitative paleolimnology (e.g., Birks, 1998), attempting to better constrain the ecological indicator value of lacustrine biotic and abiotic proxies (e.g., Eggermont et al., 2006), and using multi-proxy records to test hypotheses (e.g., Lotter and Birks 2003; Bradshaw et al., 2005). For biological proxies preserved in lake sediments (e.g., pollen, diatoms, chironomids, cladocerans, ostracods), transfer functions have been developed from calibration or training sets of modern surface sediment samples collected along environmental gradients (e.g., climate, nutrients, salinity, pH). This "calibration-in-space" approach is limited by the laborious and time-consuming analysis required. Additionally, the so-called "non-analog situations" have evoked some discussion over the past years.

With recent developments in reflectance spectroscopy scanning techniques (see contributions in this issue; Rein and Sirocko, 2002), high-resolution data acquisition has become very fast for different biogeochemical proxies and approaches. However, since lakes are biophysical systems with different configurations, transfer functions for biogeochemical sediment data cannot easily be established. The only way to transform biogeochemical sediment proxies into quantitative climate variables, therefore, is a "calibration-in-time"—a time series of well-dated abiotic sediment proxies regressed against meteorological observations (see Grosjean et al., p. 108).

This newsletter issue focuses on advances in paleolimnology, with special emphasis on recent methodological developments and their significance for research in the PAGES context.

Methodological aspects: Novel approaches and techniques

Francus et al. (p. 93) provide an overview of new X-ray fluorescence (XRF) scanning techniques that allow rapid, non-destructive acquisition of high-resolution geochemical data from sediment cores. Examples of applications include pollution detection, varve counting, and estimation of past ecosystem productivity. Brauer et al. (p. 96) present a new approach to studying annually laminated (varved) sediments, by combining microfacies analyses on thin sections with high-resolution XRF scanning on impregnated sediments. They elaborate on its potential for improved varve counting and interpretation of seasonal paleoclimate signals. Rosén et al. (p. 98) describe novel ways of extracting highly resolved information on climatic and environmental change, using non-destructive methods. They demonstrate the potential of Fourier transform infrared spectroscopy as a low-cost and effective analytical tool for the quantitative determination of biogeochemical properties from tiny sediment samples. Heiri et al. (p. 100) discuss the use of stable isotope techniques ($\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$, $\delta^{15}N$) on fossil chitinous invertebrate remains for reconstructing past climate and aquatic food webs. They highlight the need to understand diagenetic processes and their impact on the chemical composition of these fossils in the sediments. The prospect of using microbial cell membrane lipids (TEX_{86} and MBT-CBT) preserved in lake sediments as paleothermometers is discussed by Weijers et al. (p. 102), who show that these compounds are promising new proxies for reconstructing past lake water and catchment air temperatures. The use of fossil DNA preserved in the sedimentary record of lakes, and the potential of this new approach to reconstruct past changes in lake ecosystems is discussed by Coolen and Gibson (p. 104). Jeziorski et al. (p. 106) highlight the "aquatic osteoporosis" problem associated with declines in aqueous calcium commonly observed in lakes, such as the Canadian Shield. They show that Ca-rich zooplankton microfossils can help assess the ecological consequences of reduced Ca availability due to acidification, forestry, and other environmental stressors. Finally, Grosjean et al. (p. 108) discuss the importance of a reliable chronological framework in paleolimnological studies and provide a new approach with regard to ^{210}Pb profiles for depth-age modeling. Moreover, they explore the as yet rarely used "calibration-in-time" approach to infer past environmental conditions.

Regional syntheses

This newsletter also provides an overview of progress made in resolving the climate history and human impacts on lakes at a subcontinental to regional scale. Several contributions herald a PAGES initiative aimed at the high-resolution reconstruction of climate history obtained through lake records from South America, Africa, and China. Another contribution focuses on deep-sediment drilling efforts in old crater lakes. These initiatives use a number of the techniques described above, which allow for the study of global teleconnections of climate variability at timescales of 10^5 to 10^2 years, while also revealing distinct regional and/or sub-continental climate features. Such regional syntheses are crucial for establishing the spatial and temporal patterns of climate change across climatic, hydrological, and ecotonal boundaries, thereby separating climate-driven and anthropogenic impacts on ecosystems at both the site-specific and landscape scales.

Rioual and Wang (p. 110) provide a review of progress in Chinese paleolimnological studies, particularly highlighting records that trace the past dynamics of Asian monsoon systems and the Westerlies, which provide a better understanding of complex atmospheric teleconnections. Verschuren and Russell (p. 112) highlight the regionally different patterns of hydrological change during recent millennia, as reconstructed using novel temperature and moisture proxies in lakes across tropical Africa. They also demonstrate how paleogenetic tools can improve our understanding of climate-human-ecosystem interactions. García-Rodríguez et al. (p. 115) demonstrate the value of integrating data obtained through paleolimnological studies in Argentinean and Uruguayan Holocene lake records. They focus particularly on the links between past monsoonal activity and regional hydrological variability since late Glacial times in the Pampas. Finally, Pienitz et al. (p. 117) provide an update on progress in the recovery of long sediment records from continental sites and, in particular, large and deep crater lake basins. They highlight three projects funded through the International Continental Scientific Drilling Program and other partners.

The final contribution to this issue is a Program News by Gell et al. (p. 119). They report on the European Water Framework Directive and the important role paleolimnology can play in assessing ecological baseline conditions for lakes.

Outlook

The various contributions in this issue of *PAGES news* show that paleolimnology has reached a stage where high-precision data based on different proxies can be generated for lake records. Based on a vast amount of data gathered and standardized approaches, paleolimnologists are now in a position to document continent- to hemispheric-wide sensitive responses of freshwater systems to ongoing global change.

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For full references please consult:
www.pages-igbp.org/products/newsletters/ref2009_3.html

The potential of high-resolution X-ray fluorescence core scanning: Applications in paleolimnology

Pierre Francus[1], H. Lamb[2], T. Nakagawa[3], M. Marshall[2], E. Brown[4] and Suigetsu 2006 Project Members[5]

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A new generation of XRF core scanners allows rapid, non-destructive acquisition of high-resolution geochemical and X-radiographic data from lacustrine sediment cores, facilitating new approaches to many applications in paleolimnology, including pollution detection, varve counting, and estimation of past ecosystem productivity.

X-ray fluorescence (XRF) core scanning was developed in the late 1990s (Jansen et al., 1998) and is a powerful analytical technique: it is fast, requires no sample preparation, and it can detect most chemical elements of the periodic table down to limits of a few ppm, depending on acquisition dwell time and sample conditions. A new generation of XRF core scanners allowing high resolution analysis, with improved count rates and detection limits, has become widely available. One of these, the Itrax™ core scanner, takes high resolution radiographic and optical images at the same time as XRF measurements. It has a flat X-ray beam with a measurement area of 100 µm x 4 mm (or 200 µm x 8 mm), rather than a spot beam, so that grain-to-grain variance is averaged in the horizontal core axis, ensuring predominance of the environmental signal through depth (Croudace et al., 2006).

Practicalities

High-resolution non-destructive analyses of lacustrine sediments can be achieved with an XRF core scanner in a remarkably short time. For example, a 1.5 m-long core section can be scanned at 1 mm intervals in about 13 hours, with a dwell time of 30 seconds. Using a Mo X-ray tube, light elements such as Al and Si require long dwell time (>20 sec.), while heavier elements, such as Fe, Ca, Ti, are more easily detected with reduced dwell times. Numerous factors related to the sediment matrix, such as water content, organic matter, grain size, mineral crystallinity and porosity may have a significant impact on the production and the detection of fluorescent photons (Weltje and Tjallingii, 2008). Results are usually presented as spectral peak areas or counts per second (cps) and can be calibrated to concentration, although this may be cumbersome in some sediments because of the high variability of the matrix factors mentioned above. The use of element ratios and the plotting of XRF curves (in cps) together with discrete sample analyses obtained using destructive techniques, such as inductively-coupled plasma or other conventional techniques (Fig. 3a), are two ways to evade this issue. The Itrax™ core scanner also provides high-resolution X-radiographs that are useful for detecting invisible sedimentary structures.

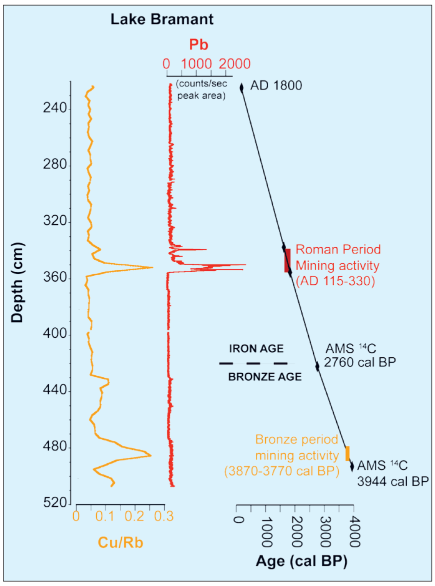

Figure 1: Lake Bramant, French Alps. Copper and lead profiles reveal metallic pollution during the Bronze and Roman periods. Age model based on radiocarbon dates (modified from Guyard et al., 2007).

Applications

XRF core scanners offer many potential applications in paleolimnology. For routine core logging, they complement other non-destructive techniques such as CT-scan and Multi-Sensor Core Logging systems (St-Onge et al., 2007). Direct applications include the detection of tephra layers and metal pollution signatures. They can also be used for provenance studies, for the reconstruction of past lake conductivity from element ratios in carbonate sediments, for estimating past weathering, leaching and erosion intensities, primary productivity, and paleo-redox conditions, as well as for sub-millimetre scale analysis and counting of fine laminations. Here, we highlight three examples of applications.

Pollution signatures

Sediment cores from high-elevation alpine Lake Bramant (western Alps, France) were logged using several techniques, including XRF scanning (Guyard et al., 2007). The analyses showed two marked increases in lead and copper concentrations (Fig. 1). The age model dated these events to around 3.8 ka BP and to AD 115-330. The former is reflecting local atmospheric pollution due to mining activity during the early Bronze Age, as confirmed by archeological evidence. The younger peak in heavy metal concentrations corresponds to the height of Roman industrial activity in the area, as recorded in historical and archeological archives. These results are supported by evidence of lead contamination at several locations in the region and from various other paleo-archives, including ice cores from Greenland (Rosman et al., 1997). Although it was not the primary goal of the study to find traces of contamination, systematic high-resolution XRF scanning revealed this important result.

Varve counting

In 2006, a new continuous 73.5 m-long sediment core was retrieved from Lake Suigetsu, Japan. The core (SG06) is rich in terrestrial plant macrofossils, providing a unique 60-ka history of atmospheric radiocarbon in an annually laminated record. The Suigetsu Varves 2006 Project will contribute to the international terrestrial radiocarbon calibration model, extending it to >50 ka. Thin-section microscopy, and high-resolution Itrax XRF and X-radiography were the two independent methods used for varve counting. Comparisons between counts from XRF-scanning and thin sections allowed internal errors to be quantified and dramatically reduced. Double-L channel core sections (Nakagawa, 2007) were scanned at 60 µm intervals, and the data analyzed with PeakCounter (http://dendro.naruto-u.ac.jp/~nakagawa/). This software was specifically developed for varve counting using multi-parameter data from the Itrax scanner. An active window selector plots up to six different parameters (e.g., radiography grey scale, selected XRF elements, or ratio between them), in separate windows using the equivalent radiograph area as the background image (Fig. 2). The active area of the optical image is also shown in a separate window, from which a grayscale plot can be derived as supporting information. A cursor line moves simultaneously in all active windows, allowing the user to mark the exact varve positions. Correlated peaks in the parameter and grayscale plots are marked with the numbers 1 to 5, denoting the counter's judgment that they represent true varves. After cross-checking against parallel thin section counts, marks at different confidence levels are counted as 1, 0.5 ± 0.5, or 0 years, following the Greenland ice core layer-counting protocols (Rasmussen et al., 2006). Most of Lake Suigetsu's varves contain an end member rich in siderite, clearly evident as peaks in Fe and Mn (the latter being incorporated into the $FeCO_3$ lattice) that coincide with optically distinct layers of high sediment density. The XRF data also allow detrital clay and tephra layers to be identified and removed from the ultimate age-depth model based on varves.

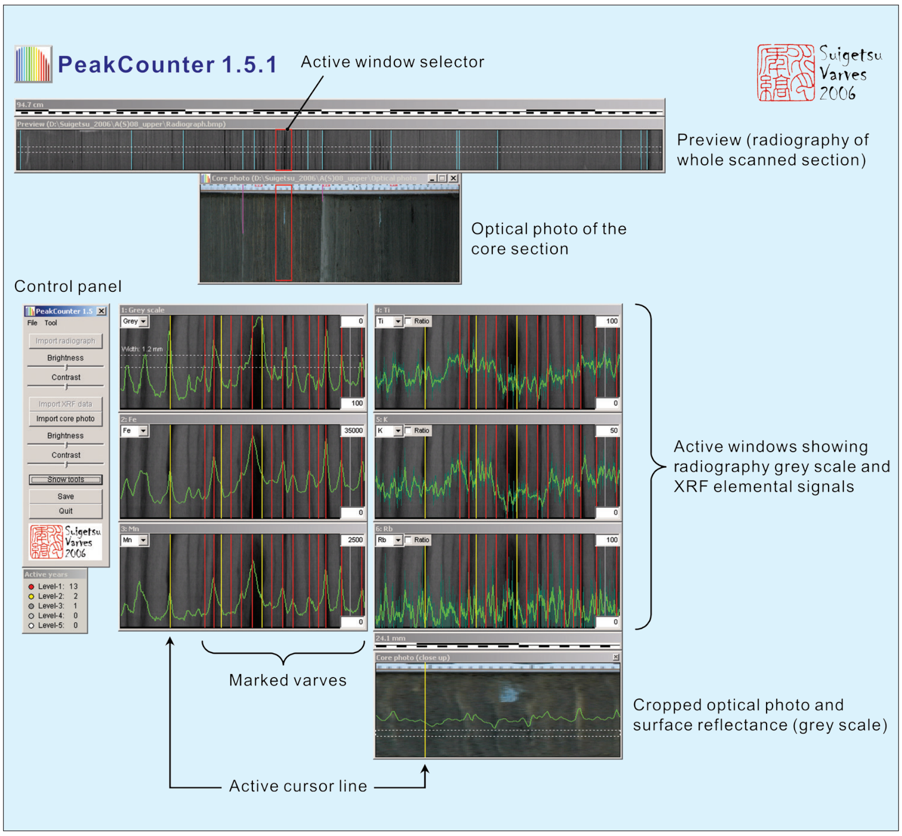

Figure 2: Screenshot views of PolyCounter 1.5, a newly developed user-friendly software for varve counting using Itrax output data files. ***Green lines*** *show XRF measurements or radiograph gray scale value (measured automatically on the image file);* ***yellow lines*** *indicate active cursor lines;* ***red lines*** *mark varve boundaries;* ***light blue*** *and* ***pink lines*** *indicate event layers, which are useful for aligning radiograph and optical photo. The installer package is available at http://dendro.naruto-u.ac.jp/~nakagawa/.*

Biogenic silica

Biogenic silica (BSi) distributions in lake sediments record variability in the productivity of diatoms and other siliceous algae, and may be used to evaluate past climate conditions in continental settings (e.g., Colman et al., 1995). Classic determination of BSi in sediments involves la-

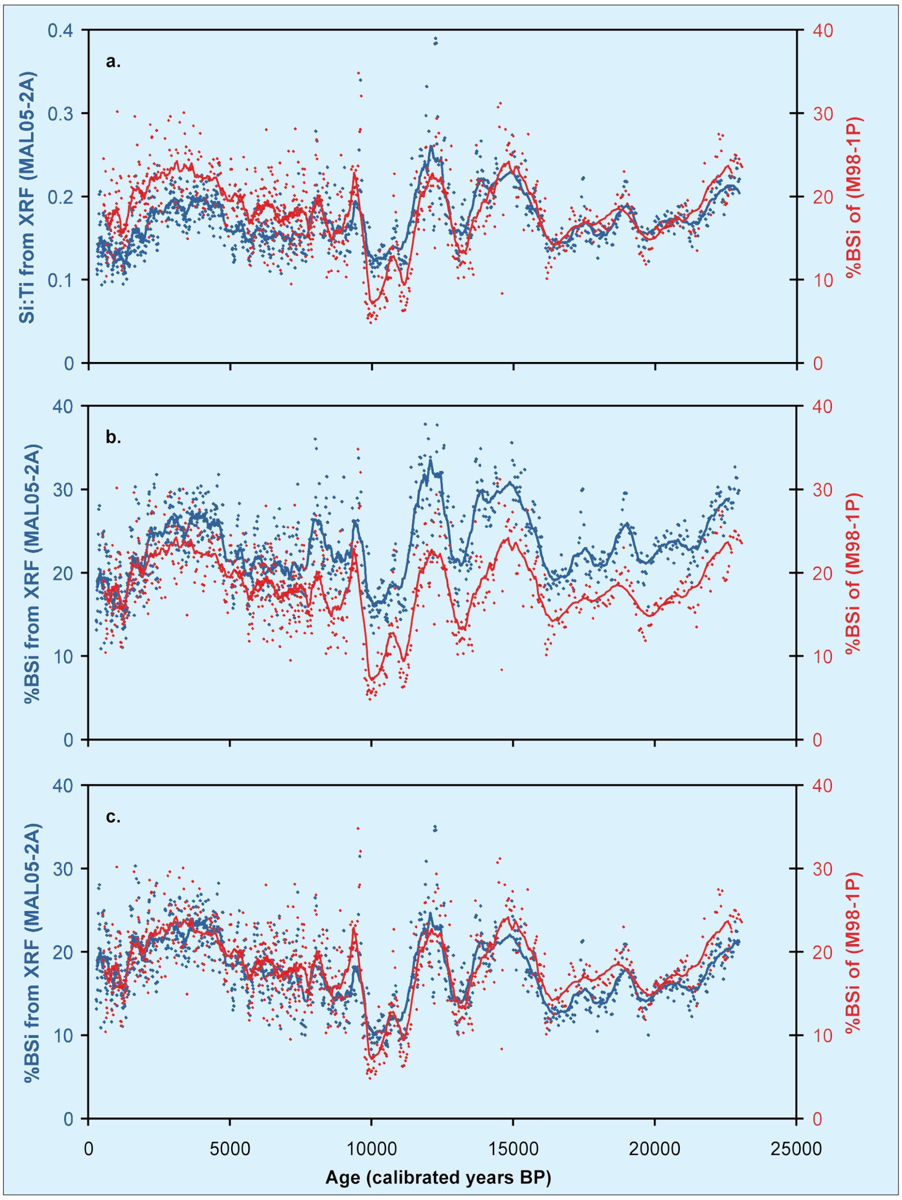

Figure 3: Application of XRF core scanning to infer %BSi in Lake Malawi sediments. ***a)*** *Comparison of uncalibrated Si:Ti$_{XRF}$ (blue) with measured %BSi (red). XRF measurements were made at 1-cm resolution in the uppermost 9 m of drill core MAL05-2A (Brown et al., 2007). %BSi was determined with 1-cm resolution for a 9-m piston core (M98-1P) taken earlier at a nearby location (Johnson et al., 2002). Records have been tuned to a common chronology. Heavy lines represent 21-point running means. %BSi determinations required nearly six months of laboratory work, while the XRF analyses were completed in less than two days.* ***b)*** *Comparison of measured %BSi with %BSi estimated from Si:Ti$_{XRF}$ using fitting parameters empirically determined for surface sediments, with values of 0.043 and 2.4 for the background and fitting terms, respectively.* ***c)*** *Comparison of measured %BSi with %BSi estimated from Si:Ti$_{XRF}$ using fitting parameters determined separately for three segments of the core (0 to 2.5 ka, 2.5 to 8.0 ka and 8.0 to 23 ka). The uppermost section used the parameters described in Fig. 3b, while the parameters for the deeper sections were determined by least squares optimization. This yielded values of 0.050 and 2.1, and 0.053 and 1.6 for the background and calibration terms, for the mid-Holocene and Late Glacial sections, respectively.*

borious sequential dissolution (DeMaster, 1979). Even with timesaving modifications (e.g., Johnson et al., 2002), a fulltime technician can process only ~40 samples in a week. The Si:Ti ratio as determined by XRF (Si:Ti$_{XRF}$) provides an efficient means of obtaining uncalibrated estimates of BSi, as shown in Lake Malawi sediments (Brown et al., 2007; Fig. 3a).

Calibration of Si:Ti$_{XRF}$ has recently become possible through fitting paired %BSi with Si:Ti$_{XRF}$ data through application of empirically determined relationships accounting for Si in clastic minerals and for dilution of clastics by high levels of biogenic material (Fig. 3b).

Comparison of a 25 ka record of measured %BSi with %BSi calculated from Si:Ti$_{XRF}$ (Fig. 3b) shows that fitting parameters determined from surface sediments may not be appropriate for the entire record, and that least squares fitting of the data in three separate core segments provides a better match (Fig. 3c). The changes in fitting parameters are consistent with generally greater exposure to chemical weathering of more recent sediments that have accumulated under relatively warm and humid Holocene conditions. These results demonstrate the great potential of this approach for providing quantitative results when appropriately calibrated.

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www.pages-igbp.org/products/newsletters/ref2009_3.html

The potential of varves in high-resolution paleolimnological studies

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A novel approach to investigating annually laminated lake sediments combines micro-facies analyses on thin sections with high-resolution X-ray fluorescence scanning on impregnated sediments. It facilitates improved varve counting and interpretation of seasonal paleoclimate signals including extreme events and the dynamics of abrupt changes.

Varved lake sediments are important high-resolution climate and environment archives for paleolimnological investigations because they provide independently datable evidence of environmental change in response to either climatic change or human impact (Lamoureux, 2001; Brauer, 2004; Zolitschka, 2003; 2006). Such records are not only found in present-day lakes but also in paleolake deposits and allow detailed reconstructions for time intervals without any human influence (Mangili et al., 2005; Brauer et al., 2007). Varved sediments provide both an independent dating tool (e.g., Kitagawa and van der Plicht, 1998) and high-resolution proxy data. Traditional geochemical, physical and biological analyses at discrete sample intervals commonly provide data at decadal to sub-decadal resolution. Annual resolution is revealed from varve thickness measurements. A comprehensive interpretation of the latter requires profound knowledge of the seasonal composition and structure of varves because many different varve types can form depending on the climate regime and environmental conditions. The classification of varves into three major types, i.e., clastic, organic and evaporitic (e.g., Zolitschka, 2003), however, is too broad to describe all variations in varve deposition. Further details about seasonal sub-layers can be obtained by micro-facies analyses (Brauer, 2004) and provide crucial information on the seasonal signals in varve records, thereby enabling the detection of low-amplitude and short-term climate changes (Brauer et al., 2008a; b). The main limitation of micro-facies data, however, lies in their only semi-quantitative character. This problem can be overcome by integrating microscope analyses with µ-XRF scanning, which allows detailed element profiling across individual varves.

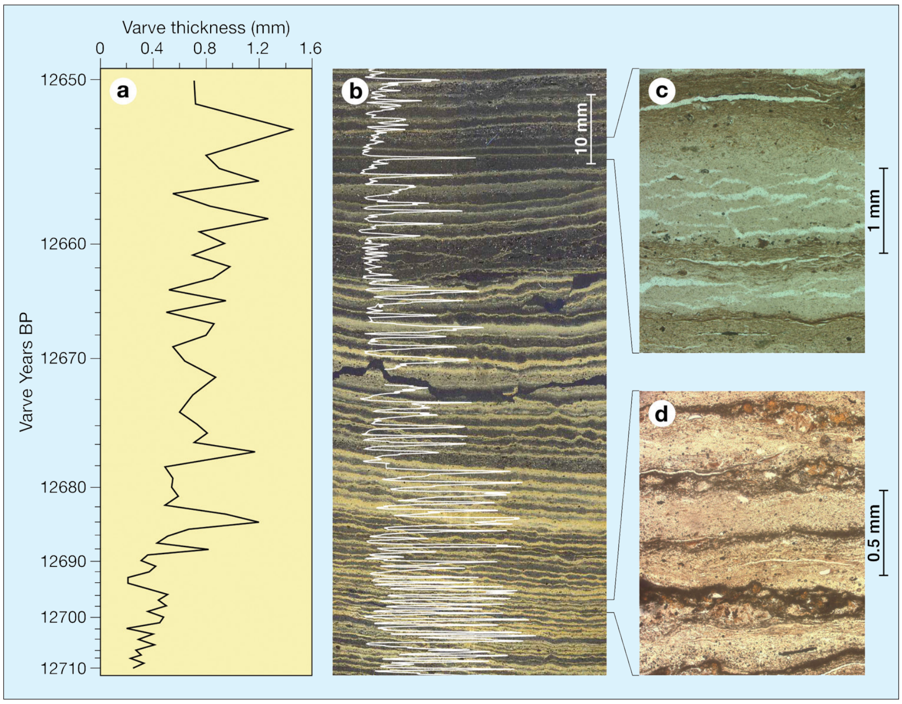

Figure 1: Abrupt micro-facies changes at the Allerød/Younger Dryas boundary (12,680 varve years BP) in the Lake Meerfelder Maar sediments. ***a)*** *Varve thickness plot (note: age scale for (a) has been adjusted to fit image (b));* ***b)*** *Thin-section scan (polarized light) and superimposed Fe-profile indicating siderite (iron carbonate)-rich winter layers (light colors); thin section images (plain parallel light) of* ***c)*** *Early Younger Dryas varves exhibiting distinct light spring/summer diatom layers and dark layers of reworked minerogenic and organic matter and* ***d)*** *Late Allerød varves characterized by dark siderite layers. Figure modified from Brauer et al., 2008a.*

Methodological approach

Direct combination of varve micro-facies data and high-resolution element scanning requires that both analyses be performed on the same sectional plane in order to exclude spatial inhomogeneities within the sediment column. Therefore, µ-XRF measurements are performed on impregnated sediment blocks that are prepared for thin section analyses. Fresh sediment slices (10 x 2 cm) are impregnated with resin after freeze-drying (Merkt, 1971) or acetone exchange (Lamoureux, 2001). The impregnated sample blocks are cut along the long axis so that the cutting plane of one half can be used for large-scale thin section preparation, while the other half serves for major element scanning. Element analyses conducted in a vacuum chamber of a µ-XRF spectrometer reduce the loss of radiation intensity due to absorption by air. Measurements at highest resolution have a spot size (beam diameter) of 50 µm and an increment of 40 µm (width between two consecutive measurements), resulting in 5 to 30 data points per varve depending on annual sedimentation rate. A further advantage of analyzing impregnated samples is the perfect reproducibility of measurements even after long storage times, because changes in sediment geochemistry are prevented by impregnation.

In conclusion, parallel micro-facies and element analyses enable unambiguous identification and allocation of each peak in element variations directly to the microscopic observation. This facilitates interpretations of the observed chemical signals and provides better quantification of micro-facies changes. Using this novel approach, it is possible to improve detection of abrupt climate changes, seasonal event layer deposition and understanding of long-term changes in seasonality.

Abrupt climate change

Abrupt climate changes are a key issue in paleoclimate research (Alley et al., 2003) because understanding the processes and dynamics of rapid and high-amplitude climate shifts is crucial for assessing the probability of such changes in the future. The last major climatic shift at the end of the last glaciation was related to the Younger Dryas cold phase, which has commonly been connected to changes in North Atlantic thermohaline circulation triggered by major melt-water fluxes (Broecker, 2006). Detailed analyses of the onset of the Younger Dryas in the varved sediment record from Lake Meerfelder Maar (Germany) provides several lines of evidence from micro-facies and elemental changes in less than a decade from a mainly quiet, anoxic lake environment to a seasonally well-mixed and turbulent lake (Fig. 1). The five-fold increase in varve thickness is explained by both higher amounts of reworked littoral material caused by strong wave activity and pronounced diatom layers as a result of increased nutrient fluxes and remobilization. Together, these data point to a very abrupt wind shift suggesting that changes in atmospheric circulation may have played a crucial role (Brauer et al., 2008a). Similar evidence for abrupt atmospheric change has been recently reported from Greenland ice cores (Steffensen et al., 2008).

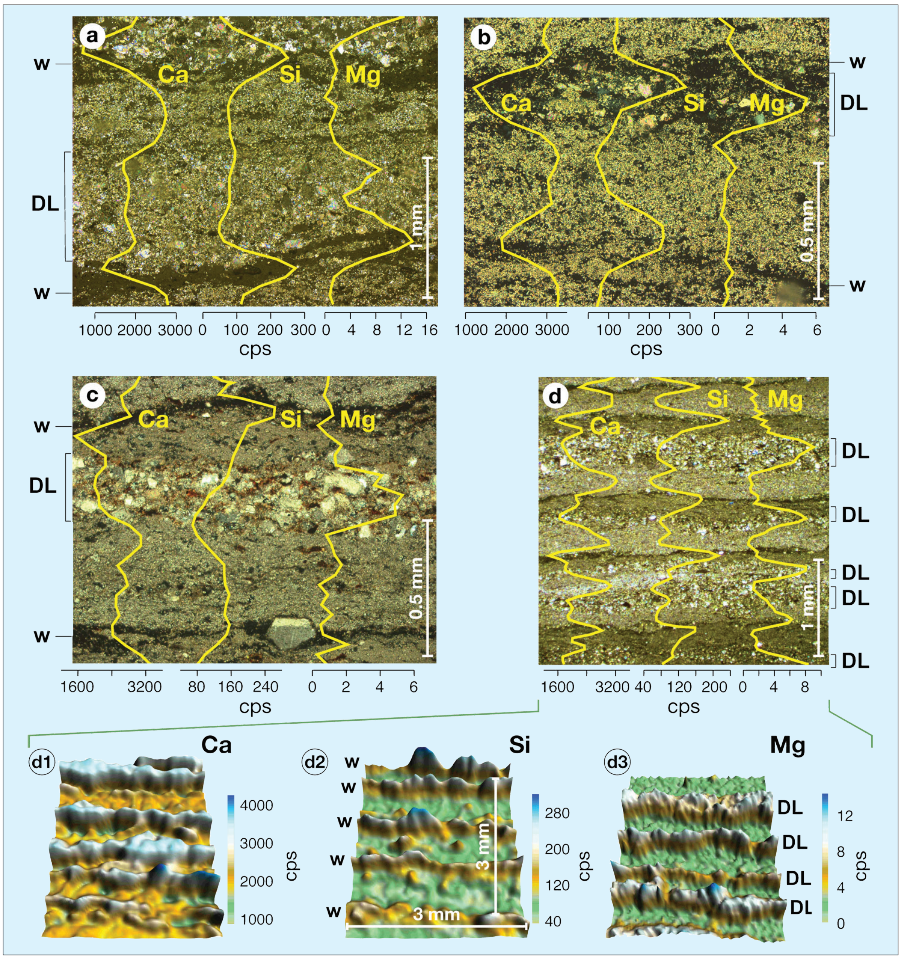

*Figure 2: Thin-section images (polarized light) of varve and detrital layers with superposed µ-XRF data at 50 µm resolution (in counts per second, cps) for intervals of the Piànico interglacial sediments. **a)** Spring detrital layer (DL) above the winter layer (w) and below the endogenic calcite layer, and profiles for endogenic calcite (Ca), siliciclastic (Si) and dolomite (Mg) detritus; **b)** Autumn/winter detrital layer (between the endogenic calcite and the upper winter layer) and element profiles; **c)** Summer detrital layer (incorporated within the calcite layer) and element profiles; **d)** Succession of 4 varves including detrital layers and element profiles; d1) – d3) 3D plots exhibiting the spatial distribution of Ca, Si, and Mg for the area shown in d). Detrital layers reflect past flood events and can therefore provide a record of the natural flood frequency from periods without human impact.*

Seasonal flood layers

A further concern in the climate debate is a possible increase in flood frequencies as a consequence of global warming. Interpretation of historical records does not provide an unequivocal picture since intense human activities in river catchments have an impact on flood characteristics and may mask climatic effects. This information gap can be filled through analyses of natural flood frequency records from periods without human impact. Varved sediments allow the seasonality of past flood deposits to be deduced through analysis of their microstratigraphic position within the annual cycle of sedimentation (Mangili et al., 2005). Mineralogical and geochemical contrasts between autochthonous sediments and flood-triggered detrital matter are distinctive features of biochemical calcite varves (Lotter and Lemcke, 1999). In a long series of such calcite varves from the interglacial Piànico paleolake (Italy, southern Alps), even micro-scale flood layers could be detected at seasonal resolution (Fig. 2). These detrital layers were composed of catchment dolomite and were therefore well distinguished from their micro-facies and geochemical signatures. Preliminary results from the study of Piànico sediments indicate that, under natural interglacial conditions, the frequencies of spring and summer floods were higher during times of colder climate (Mangili et al., 2007; 2005), whereas fall and winter floods did not show significant frequency changes.

Long-term change in seasonality

Many proxy records indicate that the Asian monsoon was intensified during the warm early Holocene climate. Thus, understanding seasonal effects and environmental processes during this time interval could aid a better assessment of future scenarios. A long varve record from Lake Sihailongwan in northeastern China enabled comparison of present-day with early Holocene seasonal dynamics through detailed micro-facies analyses. Modern varves were characterized by regular, distinct spring snow-melt layers consisting of local minerogenic and organic debris (Fig. 3; Mingram et al., 2004; Chu et al., 2005). Predominantly organic summer deposits with few minerogenic components were followed by thin autumn diatom layers. In contrast, varves that formed between 11–8 cal ka BP exhibited additional layers of well-sorted, silt-sized dust deposited in spring/early summer. These dust layers were separated from the snow-melt deposits by an additional diatom bloom (Rioual et al., 2006). The occurrence of dust layers differed from varve to varve as a result of a clear inter-annual variability of the early Holocene climate. Increased clay contents in summer and winter layers further contributed to higher minerogenic sediment fluxes compared to the present-day situation (Schettler et al., 2006).

Conclusions and outlook

There is great potential for applying µ-XRF element scanning to varve records, but the value of the huge amount of data produced can be significantly increased in combination with micro-facies analyses. Consequently, the major advance of this technique is in providing a broader database for more comprehensive interpretation rather than in reducing the time for investigation. A future challenge is to further extend the presently mainly sedimentological-geochemical database through comparably precise combinations with biological proxies.

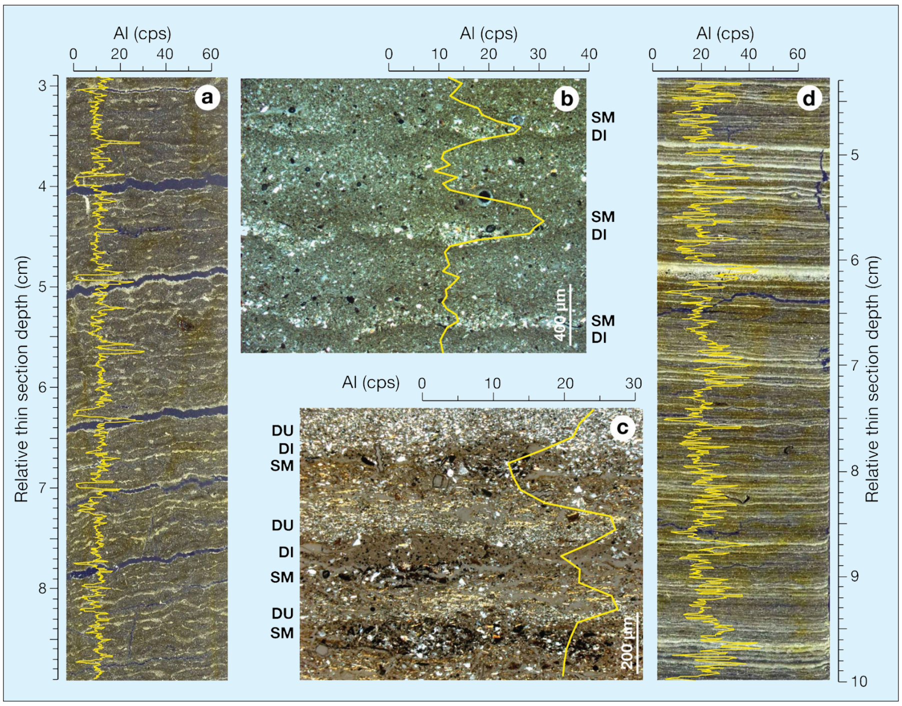

Figure 3: Comparison of modern ***(a, b)*** *and early Holocene* ***(c, d)*** *micro-facies of varves from Lake Sihailongwan, China. a) and d) show scanned thin sections (polarized light) and superposed Al-profiles as proxy for siliciclastic detritus; note the pronounced inter-annual variability in the occurrence of dust layers (light colors); b) and c) show thin section images (polarized light) showing differences in seasonal sub-layer deposition and superimposed Al-profiles: DU – dust layer; DI – diatom layer; SM – snow melt layer. Fine-grained detrital layers indicate seasons of dust deposition and can therefore provide a record of dust transport from periods without human impact.*

Note

Varve and micro-XRF Fe data from Lake Meerfelder Maar are available from the NOAA/WDC Paleo archive: ftp://ftp.ncdc.noaa.gov/pub/data/paleo/paleolimnology/europe/germany/meerfelder-maar2008.txt

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Fourier transform infrared spectroscopy: Rapid, quantitative analysis of biogeochemical properties of lake sediments

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FTIRS analysis of small sediment quantities can provide fast, inexpensive and high-resolution records of organic and inorganic carbon, nitrogen and biogenic silica that are essential for detailed paleoclimate and environmental reconstructions in long sediment records.

Continuous paleoclimate records from the continental realm covering several climatic cycles are increasingly recognized as important archives of environmental responses to climatic change. Given anthropogenic global warming, this information is particularly crucial for the understanding of natural climate variability. Over the past decade, the recovery of long sedimentary records from terrestrial sites and, in particular, large and ancient lakes, has been made possible by the International Continental Drilling Program (ICDP) and associated partners. The most recent example is Lake El´gygytgyn, where the longest (>300 m, 3.6 Ma) and probably most continuous terrestrial paleoclimate archive has been recovered during the spring 2009 deep drilling campaign. In order to extract information on climatic and environmental change from these long records at a high temporal resolution, fast, cost-efficient and, preferably, non-destructive methods are required. X-ray fluorescence scanners and multi-sensor core loggers can provide such highly resolved, qualitative and semi-quantitative information on the inorganic geochemistry, mineralogy, and magnetic properties of sediments. Non-destructive methods providing quantitative information on biogeochemical properties, however, have not been available until present. Within the initial Lake El´gygytgyn deep drilling project, and preliminary studies for potential deep drilling projects at Lake Ohrid and Pingualuit Crater Lake, we tested the potential of Fourier transform infrared spectroscopy (FTIRS) as analytical method for the quantitative determination of biogeochemical properties. The great potential of the FTIRS technique comes from the large amount of information on minerogenic and organic substances provided by the FTIR spectra. Most importantly, it is a rapid, cost-saving technique, which only requires very small amounts (0.01g dry weight) of sample material.

Analytical background and principles of FTIRS

The basic principle of the FTIRS technique is that infrared radiation stimulates molecular vibrations and, as a consequence of the quantum mechanical behavior, this radiation is absorbed at specific wavenumbers. Major changes in organic and inorganic properties present in sediment can therefore be qualitatively identified from the FTIR spectra. For example, the band

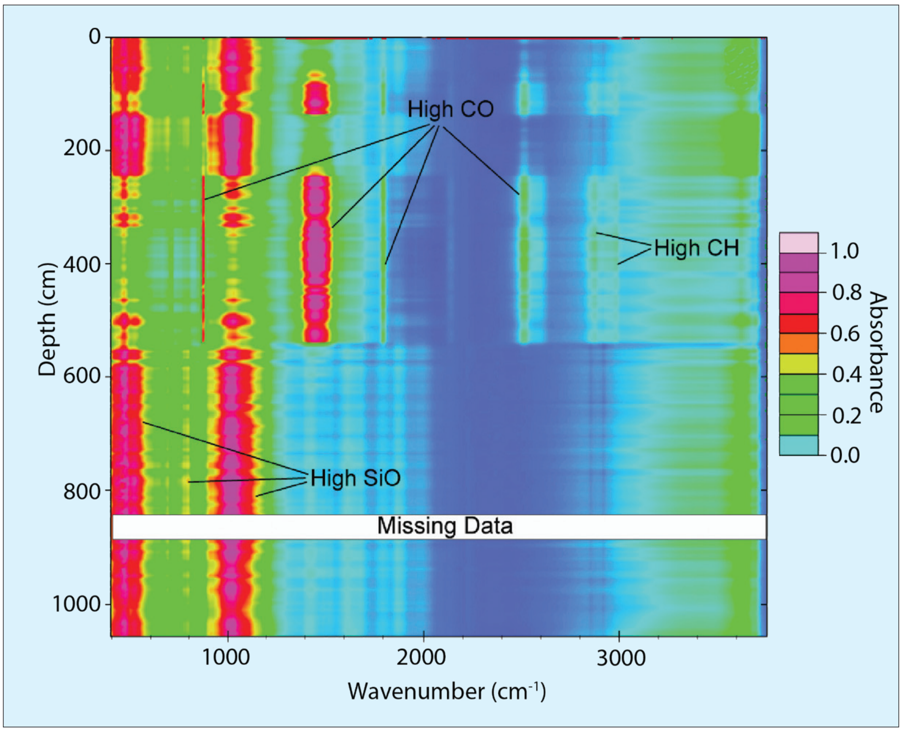

Figure 1: 2D plot of FTIR spectra from sediment core Lz1120 (Lake Ohrid, Albania/Macedonia). Wavenumbers are displayed on the x-axis, sediment depths are shown on the y-axis, and absorbance is indicated by a color chart with red/violet indicating highest and blue indicating lowest absorbance. Absorption bands for C-H stretching in organic carbon, C-O stretching in inorganic carbon and Si-O stretching in silica are indicated in the graph. The sediments show large changes within these components (from Vogel et al., 2008, with permission from Springer Verlag).

between 2850 and 2950 cm^{-1} is due to C-H vibrations in -CH_3, -CH_2 and –CH groups of organic compounds. Bands centered on 1715 cm^{-1} are assigned to the stretching vibration of the –C=O group of fatty acids (Mecozzi and Pietrantonio, 2006). Carbonate in calcite minerals has important C-O molecular vibrations around 710, 875, 1425, 1460, 1800 and 2500 cm^{-1} (White, 1974; Mecozzi and Pietrantonio, 2006; Rosén et al., 2009) and SiO in biogenic silica has an important absorbance maximum at 1100 cm^{-1} (Stehfest et al., 2005; Rosén et al., 2009). FTIRS can thus provide information on a wide range of organic and minerogenic components, e.g., carbohydrates, humic substances, silicates and carbonates (Calace et al., 1999; Stehfest et al., 2005; Mecozzi and Pietrantonio, 2006; Fig. 1). This information is of particular interest for paleolimnological studies because lake sediments are commonly composed of a mixture of various organic and minerogenic compounds originating from the fossilization of tissues and skeletons of aquatic organisms and from the erosion of lake catchment soils. Absorbance in FTIR spectra from the mid-infrared region directly relates to the concentration of specific compounds, and thus many organic and minerogenic sedimentary components can also be quantified by their own "fingerprint-like" infrared spectra. To obtain quantitative information using FTIRS, concentrations of sedimentary components measured by conventional techniques are regressed against the FTIR spectra using partial least square regression (PLS). A PLS loading plot can be compared with reference spectra of the pure component of interest, thus ensuring that the correct wavenumbers are used by the model (Rosén et al., 2009). So far, quantitative models for total organic carbon (TOC), total inorganic carbon (TIC), total nitrogen (TN), and biogenic silica (BSi) have been developed and successfully applied to lake sediments from different climatic settings (Vogel et al., 2008; Rosén et al., 2009). These promising results confirm the great potential of FTIRS as a powerful tool in high-resolution, multi-proxy paleolimnological studies.

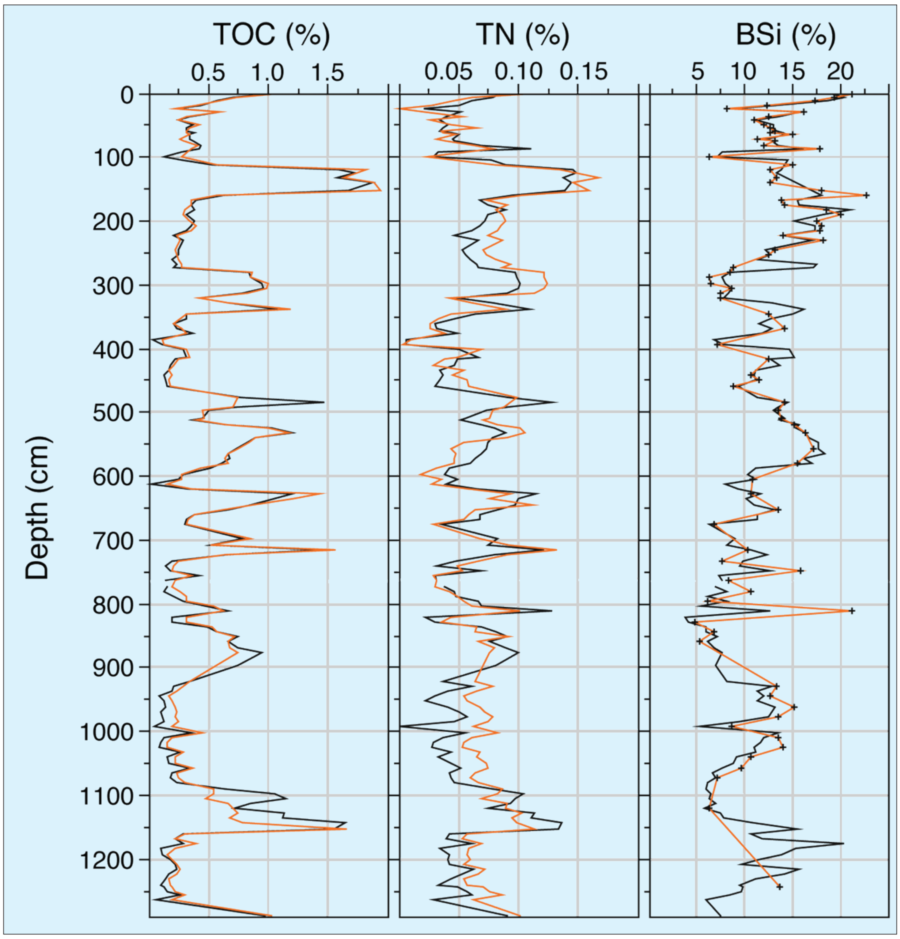

*Figure 2: Downcore plot of total organic carbon (TOC), total nitrogen (TN) and biogenic silica (BSi) within sediment core PG1351 from Lake El'gygytgyn (northeastern Siberia), measured with conventional (**orange line**) and inferred (**black line**) techniques using FTIRS. Due to the lower number of conventionally measured BSi concentrations, these samples are identified by crosses (from Vogel et al., 2008, with permission from Springer Verlag).*

Potential, limitations and examples

Interpretation of FTIR spectra can be complicated by overlapping peaks and bands that can result from the mixture of a large number of components in lake sediments. As a consequence, it is most likely that only the most common components or those with narrow absorption bands can be assessed quantitatively using FTIRS. For longer sediment records to be analyzed, for example those of ICDP deep drilling projects, with cores exceeding several hundred meters in length, the creation of a site-specific internal calibration is recommended. This technique has already been applied to sediments of lakes El'gygytgyn, Siberia, Ohrid, Albania/Macedonia and Pingualuit, Canada (Vogel et al., 2008; Rosén et al., 2009). As shown in Figure 2, FTIRS-inferred TOC, TN and BSi are plotted against values using conventional techniques and the results show a close agreement (Vogel et al., 2008). Although the results look promising, we should keep in mind that this quantitative approach has only been tested on a few lakes and we therefore recommend that some FTIRS-inferred values are cross-checked against "conventionally" measured values. With respect to the Lake El'gygytgyn sediment record, FTIRS-inferred BSi concentrations have become one of the most important proxy indicators for assessing past climatic and environmental change at fairly high-resolution back to 340 ka. In addition to quantitative assessment of biogeochemical properties, FTIRS has also been used to assess past changes in tree line and to infer lake water TOC (Rosén and Persson, 2006). After samples have been freeze-dried, ground and mixed with potassium bromide, up to 300 samples per day can be analyzed using FTIRS, which is about ten times faster compared to leaching methods (e.g., Müller and Schneider, 1993) commonly used for the determination of BSi concentrations, clearly demonstrating the advantages of FTIRS over conventional methods.

Other research areas and future applications

FTIRS is widely used in both research and industry as a reliable technique for the measurement and quality control of food and pharmaceuticals. The technique is also used in soil science to complete studies on molecular-level processes at mineral, organic, and bacterial surfaces that influence the biogeochemical cycles of elements (Schnürer et al., 2006). In recent years, the development of the FTIRS microscopy technique makes it also possible to assess specific spectra of components identified with the help of a microscope. One such example is demonstrated in Rosén et al. (2009) where spectra from single diatom valves were assessed. Thanks to the continuous technological development and improvement of FTIR spectroscopy, potential applications of the technique also continue to increase. Considering the variety of applications presented in this newsletter, we encourage more researchers to further develop this method for potential application in marine/ocean or lake sediment science.

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Stable isotopes in chitinous fossils of aquatic invertebrates

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Current stable isotope techniques permit the development of new approaches for reconstructing past climate and aquatic food webs based on chitinous invertebrate fossils from lake sediments.

Chitin is one of the most abundant macromolecules in the biosphere. It can be found in the cuticles of most invertebrates (Cauchie, 2002) and especially in exoskeletons of insects and crustaceans, where elastic chitin rods are typically embedded in and cross-linked with a matrix of proteins (Nation, 2002; Raabe et al., 2005). Organic invertebrate remains, such as exoskeleton plates, mouthparts, or sclerotized resting stages, preserve well in lake sediments (Fig. 1). After the initial decomposition of degradable material, these structures can remain chemically stable for tens of thousands of years (Stankiewicz et al., 1997a) and, in exceptional cases, chitin may even preserve for millions of years in sediments (Stankiewicz et al., 1997b).

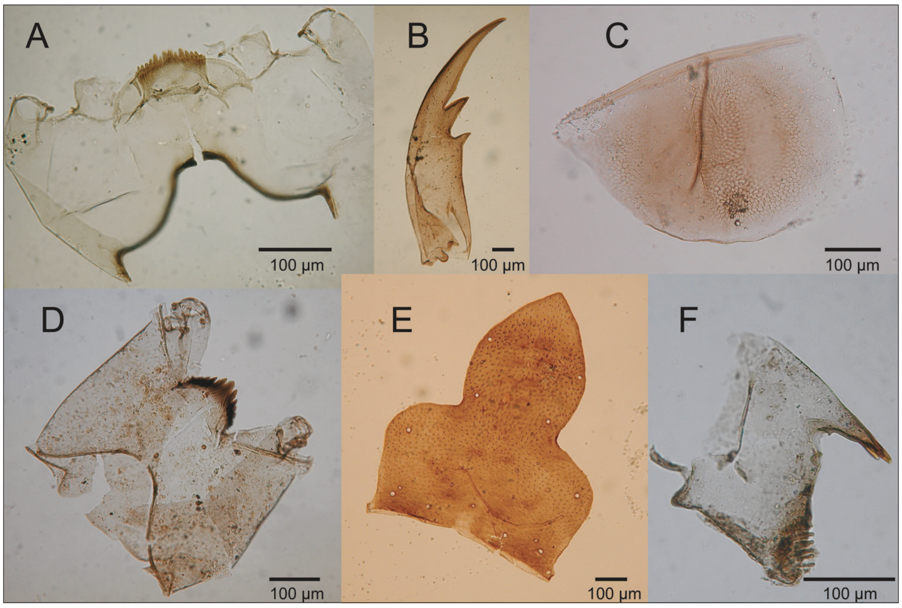

*Figure 1: Examples of chitinous fossils produced in lakes and preserved in lake sediments: Head capsules of chironomid larvae (**A**,* Polypedilum nubeculosum*-type; **D**,* Cricotopus*), mandibles of larvae of other aquatic insects (**B**, Megaloptera; **F**, Ephemeroptera), a resting egg (ephippium) of a water flea (**C**, Cladocera), and a head capsule part (clypeus) of a caddisfly larva (**E**, Trichoptera).*

Stable isotope analysis of organic material produced in lakes and their surroundings provides information on past climate and ecosystem processes within lakes (e.g., Meyers and Lallier-Vergès,

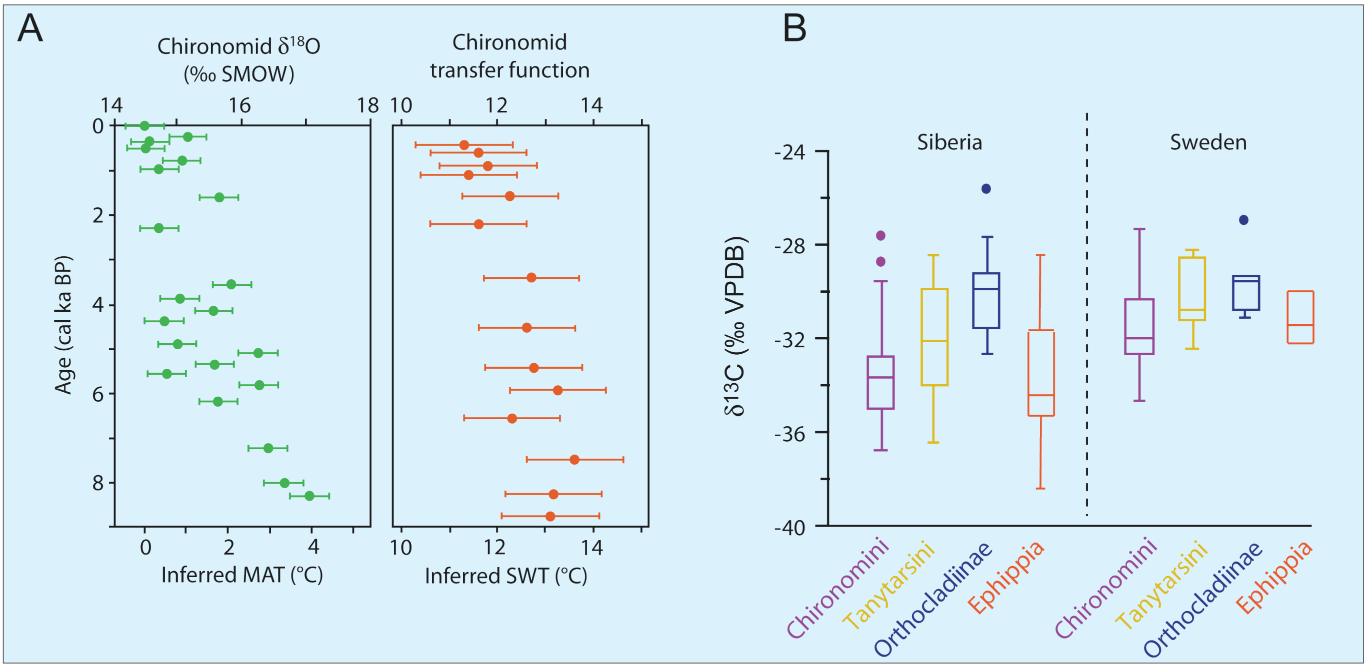

Figure 2: ***A)*** *Mean annual temperatures (MAT) reconstructed from δ18O of fossil chironomids in a Holocene sediment sequence from Qipisarqo, Greenland, compared with lake surface water temperature (SWT) inferred from the taxonomic composition of the chironomid assemblages (redrawn from Wooller et al., 2004).* ***B)*** *Taxon-specific δ13C in subfossil remains of different chironomid groups (Chironomini, Tanytarsini, Orthocladiinae) and of cladoceran resting eggs (ephippia) collected from the surface sediments of lakes in northern Siberia and Sweden (van Hardenbroek, Heiri, unpublished data). Differences in δ13C are related to the food ingested by these invertebrates with, e.g., algae typically characterized by δ13C of ~ -25 to - 30‰ (Meyers and Lallier-Vergès, 1999) and methane, which can enter food webs when taken up by methanotrophic bacteria, by values as low as ~ -50 to -80‰ (Jones and Grey, 2004). The box plots indicate the 25-75 percent quartiles (box), the median (central horizontal line), and the most extreme values less than 1.5 times the box height from the box (outer horizontal lines). Circles indicate extreme values beyond this range.*

1999; Huang et al., 2004; Wolfe et al., 2007). Organic fossils originating from invertebrates contain elements commonly analyzed in stable isotope studies, such as hydrogen, carbon, nitrogen, and oxygen (Schimmelmann, accepted). The potential of stable isotope analysis of invertebrate fossils for paleoecological reconstruction was pointed out more than 20 years ago (Schimmelmann et al., 1986; Miller, 1991). However, to date only a few attempts have been made to analyze stable isotopes in chitinous remains preserved in lake sediments. Advances in stable isotope techniques and instrumentation have significantly decreased the sample mass required for an analysis (Wang et al., 2008; van Hardenbroek et al., 2009a; 2009b). Subsequently, fossils originating from different taxonomic groups (e.g., species, genera, subfamilies) of aquatic invertebrates can be analyzed separately (e.g., van Hardenbroek et al., 2009a). This opens up a range of potential applications in paleolimnological research, which is only expected to expand in the future.

Reconstruction of past climate

The stable oxygen and hydrogen isotope composition ($\delta^{18}O$ and $\delta^{2}H$) of precipitation is strongly influenced by temperature and moisture sources. Thus, records of $\delta^{18}O$ and $\delta^{2}H$, based on material produced within lakes, can provide insights into past climate as long as the isotopic composition of the analyzed sediment component reflects the former isotopic signature of the water in which it was formed. Carbonate preserved in lake sediments has been widely used to produce $\delta^{18}O$ records of past climatic changes, reconstructing, for example, major temperature variations in Europe during the Late-Glacial period (e.g., Lotter et al., 1992; von Grafenstein et al., 1999). However, sedimentary carbonates are poorly preserved or absent in many lakes. In contrast, organic invertebrate remains are abundant in the sediments of most lakes and provide an alternative for $\delta^{18}O$ or $\delta^{2}H$ analyses. It has been shown that $\delta^{18}O$ of subfossil head capsules of chironomid larvae reflects the oxygen isotope composition of the water in which they lived (Wooller et al., 2004). Hence, $\delta^{18}O$ of fossil chironomids can be used to infer the past isotopic composition of lake water and precipitation and, indirectly, to reconstruct past temperature change (Fig. 2A). The distribution of individual chironomid species, species groups, and genera is strongly related to summer temperature. Consequently, chironomid records can also be used to develop paleotemperature estimates using numerical chironomid-temperature transfer functions (e.g., Brooks, 2006). It is therefore possible to produce multiple, independent paleoenvironmental records based on the same proxy indicator: One record based on the taxonomic composition of fossil chironomid assemblages, reflecting past summer temperatures, and another on the strong relationship between the $\delta^{18}O$ composition of fossil chironomids and mean annual temperature (Fig. 2A) (Wooller et al., 2004).

Reconstruction of past aquatic food web processes

Stable isotope analyses are widely used in food-web studies of contemporary lakes (e.g., Grey, 2006). The $\delta^{13}C$ and $\delta^{15}N$ values of aquatic invertebrates represent the isotopic composition of their food, modified by trophic level and tissue-specific fractionation factors (e.g., Martínez del Rio et al., 2009). Similarly, $\delta^{2}H$ of aquatic insects also seems to reflect the isotope composition of their diet (Wang et al., 2009). Chitinous fossils of aquatic invertebrates contain carbon, nitrogen, and hydrogen, allowing measurements of $\delta^{13}C$, $\delta^{15}N$ and $\delta^{2}H$, and can be used to reconstruct past feeding ecology. For example, it has been demonstrated that $\delta^{13}C$ can be reliably measured on fossil head capsules of chironomid larvae (e.g., Wooller et al., 2008) and that these measurements reflect $\delta^{13}C$ in the food available for larval growth (van Hardenbroek et al., 2009a). In lakes, chironomid larvae show a wide range of $\delta^{13}C$ values depending on whether they feed predominantly on organic matter generated in the photic (photosynthetically active) zone of lakes, or whether the larvae ingest and incorporate methane-derived carbon (i.e., from methanotrophic microorganisms) (Jones et al., 2008). Results indicate that $\delta^{13}C$ differs between chironomid fossils originating from different taxa present in Swedish and Siberian lakes (Fig. 2B). Fossils of Chironomini, a group with many species whose larvae live in and burrow into the sediments, tend to have lower $\delta^{13}C$ than other groups (e.g., Tanytarsini, Orthocladiinae), suggesting that methanotrophic bacteria play a more important role in their diet than in the diets of other chironomids. This finding, together with the observed low $\delta^{13}C$ in tissue and fossils of other aquatic invertebrates, such as cladocerans (water fleas) (Kankaala et al., 2006; Fig. 2B), suggests that carbon derived from methanotrophic bacteria can be consumed by a range of invertebrate groups where methanotrophic bacteria are an available food source in lakes. Hence, $\delta^{13}C$ of fossil aquatic invertebrates can provide insights into the past availability and importance of methanotrophic microorganisms in different parts of lake ecosystems and, indirectly, on past methane production and oxidation in lakes (van Hardenbroek et al., 2009a). Similarly, analyses of aquatic invertebrate $\delta^{15}N$, and especially the comparison of $\delta^{13}C$ and $\delta^{15}N$, can provide valuable information on changes in the past trophic position of invertebrate groups within lacustrine food webs.

Future directions

Analytical methods available for analyzing stable isotopes in organic remains of aquatic invertebrates have progressed to the stage where fossils of individual taxa (e.g., species, genera, or subfamilies) can be measured. This allows inferences to be made in respect to past environmental conditions in different parts of lake ecosystems and about past food sources and the past trophic position of aquatic invertebrate taxa. However, the structural integrity of organic microfossils does not guarantee that the chemical composition of these structures has not been altered by degradational or diagenetic processes. Efforts are necessary to assess how degradation potentially affects the stable isotopic composition of these fossils. Moreover, fractionation processes associated with intake of diet and water by aquatic invertebrates need further detailed investigations. In particular, the complex biochemical reactions associated with the formation of the invertebrate exoskeleton could influence the stable isotopic composition of fossilizing structures. Laboratory experiments studying stable isotopes in aquatic invertebrates and their fossilizing structures in respect to the isotopic composition of their food (e.g., van Hardenbroek et al., 2009a) and of lake water (e.g., Wang et al., 2009) are therefore needed to better constrain the interpretation of these stable isotope records from sediments. To develop this approach further, datasets that document the stable isotope composition of aquatic invertebrates in lakes, covering a wide range of environmental conditions, will be necessary. It can be expected that such detailed calibration datasets will allow quantitative paleoenvironmental reconstructions based on stable isotopes of fossil invertebrate remains, and significantly expand both the applicability and reliability of this new approach.

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Microbial membrane lipids in lake sediments as a paleothermometer

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New organic geochemical technique has potential for reconstructing absolute lake surface and lake catchment temperatures in paleolimnological studies

Lake sediments are an essential source of data on past climate change on the continents. Paleolimnological techniques designed to reconstruct continental temperature changes have primarily focused on carbonate sources and oxygen isotopes in biogenic silica (e.g., von Grafenstein et al., 1994; Rietti-Shanti et al., 1998). Transfer functions aimed at absolute temperature reconstructions from biological records are promising for pollen and chironomids (e.g., Walker et al., 1991; Lotter et al., 1997). Obviously, not all lake records contain carbonates, chironomids or pollen. Clearly, it is desirable to have different tools at hand for temperature reconstructions as the best reconstructions are to be obtained by means of multi-proxy approaches. An opportunity to expand this proxy "toolbox" comes from microbial cell membrane lipids, which might be used to reconstruct lake surface water temperatures and catchment air temperatures.

Lake surface paleothermometer

Because of their wide application in marine environments, considerable interest has developed in recent years for the application of isoprenoid Glycerol Dialkyl Glycerol Tetraether (GDGT) membrane lipids as temperature indicators of lakes. In the marine environment, these lipids are synthesized by pelagic non-thermophilic Crenarchaeota and the degree of internal cyclization of GDGTs, expressed in the TEX_{86} (TetraEther indeX of molecules containing 86 carbon atoms) shows a strong relation with sea surface temperature (Schouten et al., 2002; Kim et al., 2008). This proxy has since found many applications in marine sediment records (e.g., Sluijs et al., 2006). Further, preliminary analyses of surface sediments from four globally distributed large lakes by Powers et al. (2004) demonstrated the presence of crenarchaeotal GDGTs, and thus showed potential for application of TEX_{86} in lacustrine systems. The initial calibration curve of TEX_{86} in lakes, based on comparison of the GDGT composition of lake surface sediments with published mean annual

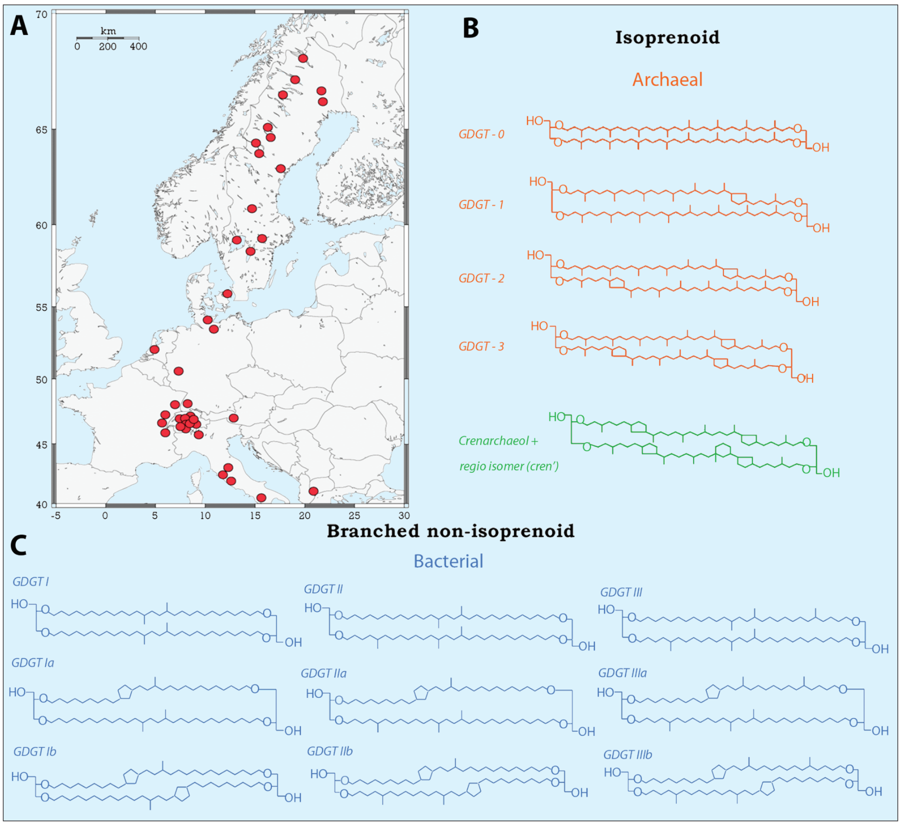

*Figure 1: **A**) Location map of European lakes (left) investigated for the presence of different types of Glycerol Dialkyl Glycerol Tetraether (GDGT) membrane lipids (right). Redrawn from Blaga et al. (2009). **B**) GDGTs 1, 2, 3 and the regio-isomer of crenarchaeol (cren'; a different stereochemical structure) are used in the TEX_{86} lake surface temperature proxy. Both crenarchaeol and its regio-isomer are uniquely synthesized by Crenarchaeota, whereas the other GDGTs (0-3) could also be produced by other Archaea, e.g., methane producing Euryarchaeota. **C**) Branched GDGTs (I-III) are synthesized by as yet unknown bacteria predominantly occurring in soils and peat. The abundance of these branched GDGTs relative to Crenarchaeol (the Branched vs. Isoprenoid Tetraether (BIT) index) is a measure of the relative input of soil organic matter to aquatic sediments. The degree of branching (GDGTs I-III) and the degree of cyclization (GDGTs a-b) of these GDGTs are reflecting both annual mean air temperature and soil pH.*

lake surface water temperatures (LSTs), was almost identical to the one obtained by Schouten et al. (2002) for the marine system. Using this calibration, down-core applications of TEX_{86} in lakes have been described for Lake Malawi and Lake Tanganyika (Powers et al., 2005; Tierney et al., 2008). In order to extend the calibration curve for TEX_{86}, Blaga et al. (2009) analyzed surface sediments from 47 lakes distributed over a temperature gradient in Europe (Fig. 1). This study indicated that the relationship between TEX_{86} and LST in lacustrine environments may be hampered by several factors.

Sources of GDGTs in lakes

Of crucial importance for the GDGTs found in lake sediments is that their origin is not necessarily restricted to a single group of Archaea. Next to the aquatic Crenarchaeota, which produce the TEX_{86} signal, soil Crenarchaeota and Euryarchaeota (mainly methanogenic Archaea) also synthesize some of the lipids used in TEX_{86} (Wakeham et al., 2003; Weijers et al., 2006). The ternary diagram in Figure 2 shows the distribution of the major GDGTs in sediments from the European lakes, as well as in soils and marine sediments. Crenarchaeol is uniquely synthesized by Crenarchaeota, whereas GDGT-0 is synthesized by both Crenarchaeota and methanogenic Euryarchaeota. Branched GDGTs are a different class of GDGT lipids synthesized by bacteria predominantly occurring in soils and peat. The Branched vs. Isoprenoid Tetraether (BIT) index is a measure for the relative input of soil organic matter (OM) to aquatic sediments, i.e., BIT values near 0 and 1 indicate a predominance of aquatic and soil OM, respectively. Figure 2 shows that the GDGT composition in lake sediments with a high BIT index is similar to that observed in soils and thus these lakes likely receive a considerable fraction of GDGTs from soil Crenarchaeota, which obstructs the use of TEX_{86} (Weijers et al., 2006). In lakes where the GDGT-0 vs. crenarchaeol ratio is >2, methanogenic Euryarchaeota are likely an additional source of GDGT-0 next to aquatic Crenarchaeota. Lakes plotting in the red boxed area of Figure 2 defined by a BIT index <0.4 and a GDGT-0/crenarchaeol ratio <2 have potential for TEX_{86} paleothermometry. The linear relationship between TEX_{86} and LST could be established for 8 lakes. Based on these lakes, the relation suggests that the values of the proxy might reflect winter temperatures rather than mean annual temperatures, but molecular ecological studies of lakes are required to confirm this.

Sediment traps

Support for the potential, and a clarification of the constraints of TEX_{86} applications in lakes is provided by a recent study involving a sediment trap in African Lake Challa (Sinninghe Damsté et al., 2009). TEX_{86} values derived from sinking particulate OM collected at 35m depth in the water column correctly reflect in situ ambient water temperatures of the oxygenated part of the water column. TEX_{86} values of contemporary lake surface sediments, however, were obscured by a contribution of similar GDGTs most likely derived from deep-water anaerobic Archaea, and therefore do not reflect LST. These and previous results illustrate that the full complement of GDGTs necessary to calculate TEX86 values is present in many lakes, and thus show promise for the reconstruction of LSTs. However, these studies also demonstrate that the source of GDGTs in lake sediments should be well constrained before applying the TEX_{86} paleothermometer.

Lake catchment paleothermometer

Where a large soil OM flux complicates use of TEX_{86}, it could provide an opportunity to apply another recently developed temperature proxy based on the branched GDGT lipids derived from soils. These GDGTs, synthesized by as yet unknown bacteria, differ in the amount of rings and branches in their carbon structure (Fig. 1). Comparison of branched GDGT distributions in >100 worldwide distributed soils with environmental parameters showed that their composition is determined by both soil pH and annual mean air temperature (MAT). This relation led to the development of the MBT-CBT proxy (Methylation index and Cylcization ratio of Branched Tetraethers, respectively) for MAT, which has been successfully applied in marine sediment archives (Weijers et al., 2007a; b; c). Therefore, this proxy bears potential for application in lake sedimentary archives to reconstruct MATs of the lake catchment area. Preliminary analysis of some lake sediments showed promising results, e.g., Lago di Vico (Italy) and a small lake from Brazil, where reconstructed MATs are close to measured MATs from nearby weather stations (Blaga et al., unpublished). Also in a long sediment core from Valles Grande Caldera in New Mexico (USA), the MBT-CBT proxy captures glacial-interglacial transitions and matches the pollen records from this lake (Werne et al., unpublished). In some other cases, however, re-

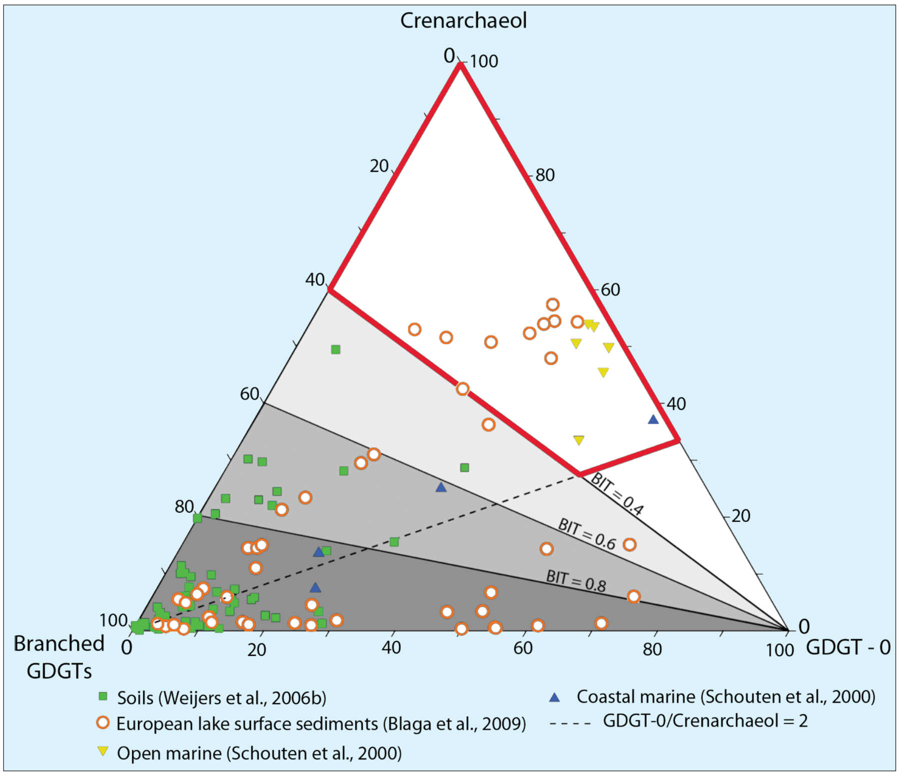

Figure 2: Ternary diagram showing the relative distribution of the three main types of GDGTs (drawn in Fig. 1) in different sedimentary environments. Lakes plotting in the red boxed area have potential for application of the TEX_{86} proxy. See text for further explanation. Adapted from Blaga et al. (2009).

constructed MATs from surface sediments seem to be lower than measured MATs. An explanation for this mismatch could be the production of branched GDGTs in situ in lake sediments, which are in fact aquatic soils. Recently, this possibility has indirectly been shown for sediments from a fjord (Peterse et al., 2009) and two tropical lakes (Tierney and Russel, 2009; Sinninghe Damsté et al., 2009) by a different distribution of branched GDGTs in these sediments than in soils surrounding the fjord and lakes. This indicates that estimated MATs based on branched GDGT distributions in lake sediments with high in situ GDGT production might be biased towards lake bottom water temperatures.

Conclusions

Both organic geochemical paleothermometers, TEX_{86} and MBT-CBT, are promising new proxies for reconstructing LST and MAT, respectively, from the GDGT lipid distribution in lake sediments. Care should be taken, however, where these proxies are applied: TEX_{86} seems mainly applicable in larger lakes that receive little soil OM input and do not contain large communities of methane-producing Archaea, whereas MBT-CBT seems to be most useful in lakes that do receive a large influx of soil OM relative to in situ production of branched GDGTs in the lake sediments.

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Ancient DNA in lake sediment records

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Ancient DNA in lake sediments offers a novel window into past aquatic ecosystems and the environmental changes that triggered past species successions.

The geological record offers our best opportunity for understanding how biological systems function over long timescales and under varying paleoenvironmental conditions. Understanding these ecosystem responses to change is critical for biologists trying to understand how organisms interact and adapt to environmental changes, and for geologists seeking to use these biology-geology relationships in order to reconstruct past climate conditions from sediment records. For example, enumeration of microscopic fossilizing protists, such as diatoms, has become a standard paleoecological approach in the fields of paleoclimatology and paleolimnology. However, the identification of morphological remains is not always straightforward, as many taxa lack diagnostic features preserved upon fossilization. Lipid-based records can be particularly valuable for species that do not leave diagnostic features in the sedimentary record. Nevertheless, the interpretation of these molecular stratigraphic records is often complicated by the limited specificity of many lipid biomarkers.

There is thus a need to find new biomarkers with greater source-specificity that can be used to complement and enhance interpretations based on existing methods. The field of molecular biology offers a most promising approach/technique that is just starting to gain wider utility: The use of ancient DNA preserved in the sedimentary record (i.e., fossil DNA or *f*DNA) to reconstruct past ecosystems. Fossil DNA has been successfully employed to study the succession of species as a result of environmental changes in terrestrial (e.g., Willerslev et al., 2007), marine (Boere et al., 2009; Coolen et al., 2007; 2009; Coolen and Overmann, 2007; Manske et al., 2008), and lacustrine settings (Bissett et al., 2005; Coolen et al., 2004; 2008; Coolen and Overmann, 1998; D'Andrea et al., 2006; Epp et al., 2009). A major advantage of this molecular paleoecological approach is that ancient species can be studied, including those with-

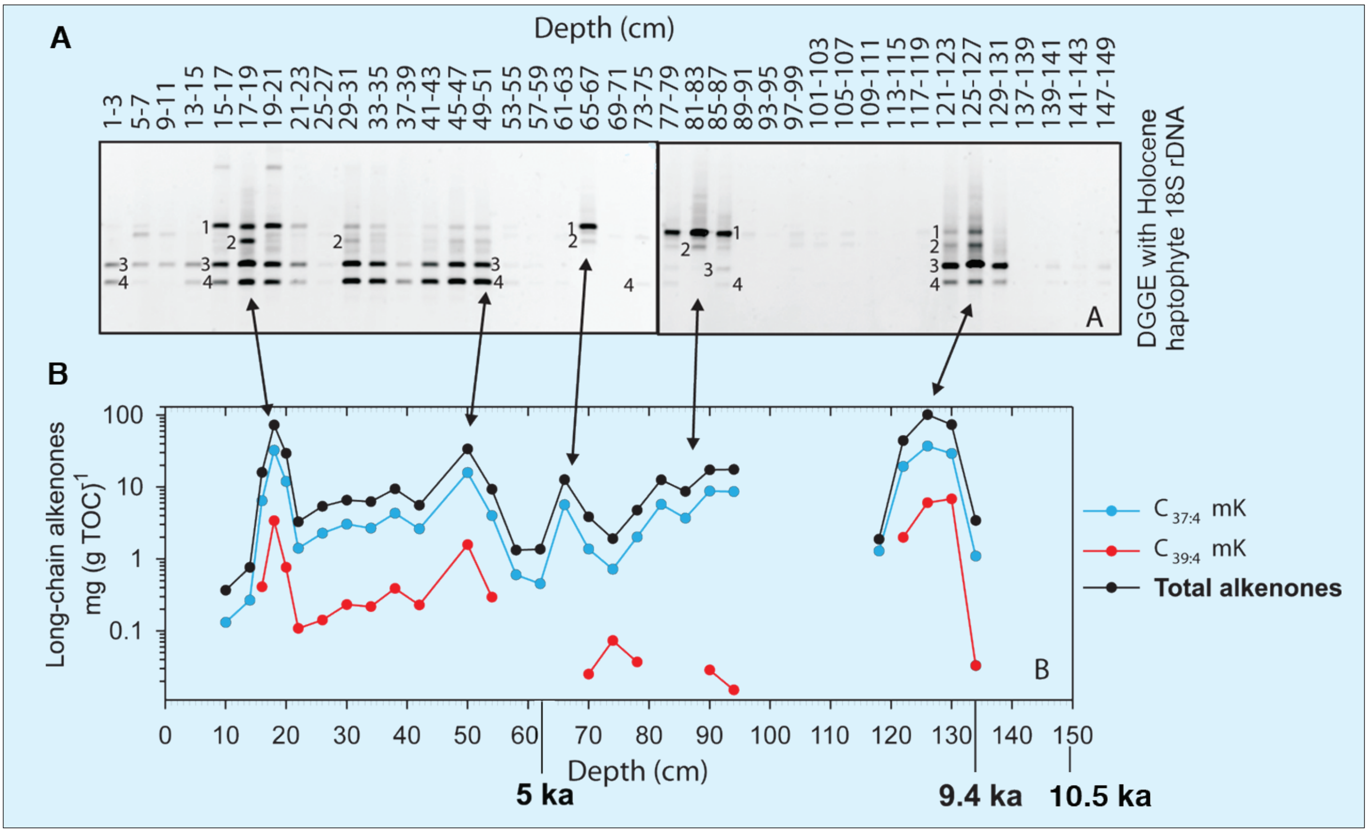

*Figure 1: Stratigraphy of biomarkers of photosynthetic haptophyte algae (18S ribosomal DNA, alkenones [mK, methyl ketone]) recovered from the Holocene sediments of Ace Lake (figure modified from Coolen et al., 2004). (**A**) Denaturing gradient gel electrophoresis (DGGE) gels with PCR-amplified 18S rDNA of Holocene haptophytes. DGGE bands numbered as 1 to 4 were excised from the gel and subsequently sequenced for phylogenetic analysis (Coolen et al., 2004). All sequences were related to non-calcifying* Isochrysis *spp. (data shown in Coolen et al., 2004). (**B**) Quantity of total alkenones produced by* Isochrysis *spp. (black line), the most predominant alkenone (i.e., the 4 times unsaturated C37:4mK; blue line), and C39:4 mK (red line) [mg (g^{-1} TOC)]. TOC = Total Organic Carbon. Comparable profiles were found for other alkenones that were produced by the* Isochrysis*-related haptophytes (see Coolen et al., 2004). The oldest analyzed sediment layer was deposited at 10.5 ka BP when the lake was freshwater, but the first haptophytes appeared at the onset of meromictic conditions when the lake became a marine basin and salinity reached 10 psu at 9.4 ka BP. The marine basin became an isolated saline lake at ~5 ka BP. Parallel examination of the alkenones and haptophyte sequences, especially from sediments deeper than 65 cm, revealed that the less common C39:4 mK was not biosynthesized by phylotype 1. The species-specific identification of alkenone sources is important for the calibration of alkenone-based SST reconstructions. See Coolen et al. (2004) for further details.*

out diagnostic features retained in the fossil record.

Study sites and analytical approaches for *f*DNA studies

Most *f*DNA surveys have been conducted on Holocene lake sediments that were deposited under cold and/or anoxic conditions. In particular, permanently stratified (meromictic) lakes with anoxic bottom waters and undisturbed laminated sediments provide excellent preservation conditions for *f*DNA. The strong vertical stratification of (microbial) species in meromictic environments makes it easier to identify species that are and were indigenous to the surface waters.

However, despite excellent preservation conditions, the degradation of ancient DNA to shorter fragments occurs within the first several thousands of years after deposition (Coolen and Overmann, 1998). Therefore, only short, less than 500 base pair (bp)-long *f*DNA fragments should be analyzed using molecular methods that involve polymerase chain reaction (PCR; a technique used to amplify DNA across several orders of magnitude to yield billions of copies of a particular DNA sequence of interest). Furthermore, the use of group-specific oligonucleotides (i.e., primers, which serve as a starting point for PCR) instead of universal primers significantly lowers the detection limit of *f*DNA during PCR. Identification of the ancient species composition most commonly involves the separation of PCR-amplified *f*DNA by denaturing gradient gel electrophoresis (DGGE) and subsequent phylogenetic analysis of sequenced DGGE bands (e.g., Boere et al., 2009; Coolen et al., 2004; 2007; 2008; 2009; Manske et al., 2008). DGGE is a fast and inexpensive way to analyze 200 to 500-bp-long PCR-amplified *f*DNA. We recently started to perform parallel phylogenetic surveys of reverse transcribed and PCR-amplified gene transcripts from the environmental samples (Coolen and Shtereva, 2009). Species that express genes in deep anoxic waters and sediment samples at the time of sampling are considered to be metabolically active and indigenous to those samples, and are therefore excluded as proxies for past environmental conditions of the surface waters. In order to further ground-truth *f*DNA data, we always perform a parallel analysis of the more traditional (morphological) proxies (Boere et al., 2009).

*f*DNA in Antarctic lakes: Protists and photosynthetic bacteria

Ace Lake (Vestfold Hills, Antarctica) was originally a freshwater lake. Due to sea level changes resulting from Holocene deglaciation, the lake became a meromictic saline fjord system with sulfur-rich bottom waters at 9.4 ka BP, and then a saline, meromictic lake about 5 ka BP (Cromer et al., 2005; Coolen et al., 2006). We expected these major hydrologic changes to have a strong impact on the ancient pelagic communities of the lake. The onset of photic zone anoxia at 9.4 ka BP was verified from the presence of *f*DNA and carotenoids of anoxygenic photosynthetic green sulfur bacteria, which still inhabit the sulfidic chemocline of Ace Lake today (Coolen et al., 2006). Furthermore, this freshwater/fjord transition was marked by a shift in pelagic cyanobacteria to a predominance of a *Synechococcus* strain (Coolen et al., 2008) that is still abundant in Ace Lake and which requires a minimum salinity of 10 psu for growth. The passing of a critical salinity threshold also resulted in the occurrence of non-calcifying alkenone-biosynthesizing haptophytes related to coastal *Isochrysis* species (Coolen et al., 2004; Fig. 1). Alkenones are of great interest to paleoceanographers because of the strong empirical relationship between the degree of unsaturation in alkenones and growth temperature, which forms the basis for their use as a molecular proxy of past sea surface temperatures (SST) (e.g., Brassell et al., 1986). Based on the phylogenetic information inferred from *f*DNA, it should be possible to calibrate the reconstructed alkenone-based Holocene SST in eastern Antarctica once modern cultivars related to the Holocene haptophytes become available. Thus, the *f*DNA analysis served to identify past (morphologically non-fossilizing) species with clearly defined paleoenvironmental growth requirements, as well as biological sources of fossil lipid biomarkers.

*f*DNA in Antarctic lakes: Ancient copepods

The lack of diagnostic features is not restricted to unicellular aquatic organisms but can also be the case for metazoans. For example, the best preserved copepod remains present in lake sediments are eggs, which often have few if any distinguishing features. Therefore, the *f*DNA approach was developed to track changes in ancient copepod diversity in lakes (Bissett et al., 2005). This approach allowed the characterization of copepod species in sediments from three fresh to brackish Antarctic lakes as old as 10 ka BP. In most cases, the fossil species found matched those of extant lake populations, but analysis of early- to mid-Holocene sediments from one lake revealed a species that is not known to exist today (Gibson and Bayly, 2007). It was furthermore shown that it is possible to recover copepod DNA from lake sediments that underwent long-term refrigeration (4°C) or preservation in polyethyleneglycol (Bissett et al., 2005).

Potential of this new approach

It is obvious that *f*DNA can be used to: (a) study the succession of a large variety of ancient species with defined environmental requirements, including those that lack diagnostic features, (b) identify biological precursors of (lipid) biomarkers, and (c) verify paleoenvironmental information (i.e., alkenone SST) inferred from (lipid) biomarkers. However, the extent to which *f*DNA is preserved and the factors/conditions that control the preservation (survival) of DNA remain largely unknown. These and other issues must be addressed and resolved before *f*DNA techniques can be broadly applied, especially in non-polar lakes. In addition, many group-specific PCR/DGGE runs are required to cover the total diversity of ancient species. We therefore recently explored the use of parallel tag-encoded amplicon pyrosequencing (Sogin et al., 2006) as a molecular paleoecological tool. Price reduction and easier and faster computing of the gigantic sequencing datasets should eventually make pyrosequencing the standard method for *f*DNA studies, thereby replacing currently used molecular methods.

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Tracking the effects of "aquatic osteoporosis" using paleolimnology

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Recent but widespread observations of aqueous calcium (Ca) declines in softwater lakes/ponds have spurred research on Ca-rich crustacean zooplankton as paleoindicators of the ecological consequences of Ca declines attributable to acidification, forestry, and other environmental stressors.

Emergence of calcium decline as an ecological stressor?

Understanding the ecological consequences of acid deposition has been an environmental topic of interest for many years. Recently, the focus of study in affected areas has shifted from an examination of impacts of pH decline to an evaluation of the effectiveness of current emission controls and the detection of recovery. In softwater regions, chemical recovery in lakes has generally been slower than anticipated (Stoddard et al., 1999; Jeffries et al., 2003). A common explanation for this muted response has been the depletion of base cations (principally Ca) from watershed soils, and a subsequent decline in lakewater Ca concentrations that counteract the reduction in sulfate inputs (Kirchner and Lydersen, 1995; Likens et al., 1996). Moreover, it is now clear that many ecosystems are being subjected to the effects of multiple stressors, and some of these might exacerbate Ca decline. Given the lack of reliable long-term monitoring data, paleolimnological approaches are being used extensively in the study of a wide variety of lake management issues (Smol, 2008). The mechanisms driving Ca depletion in soils are thought to be a site-specific combination of accelerated release due to acid rain (Stoddard et al., 1999), and forest regrowth following biomass harvesting (Watmough et al., 2003). Reduced atmospheric Ca inputs may also contribute to depleted soil Ca pools. In the softwater lakes and ponds of the Canadian Shield in North America, declines in Ca concentrations of up to 40% below 1980s levels have been observed (Jeziorski et al., 2008a). As Ca is an essential nutrient, there has been growing concern that Ca levels may be approaching concentrations low enough to constitute an environmental stressor in their own right. This is especially the case for those aquatic invertebrates that have relatively high Ca demands due their use of Ca biominerals as structural elements in their exoskeleton.

Although there is a general understanding of the mechanisms driving Ca decline, we are faced with a widespread lack of baseline or pre-impact reference conditions, because the long-term causes

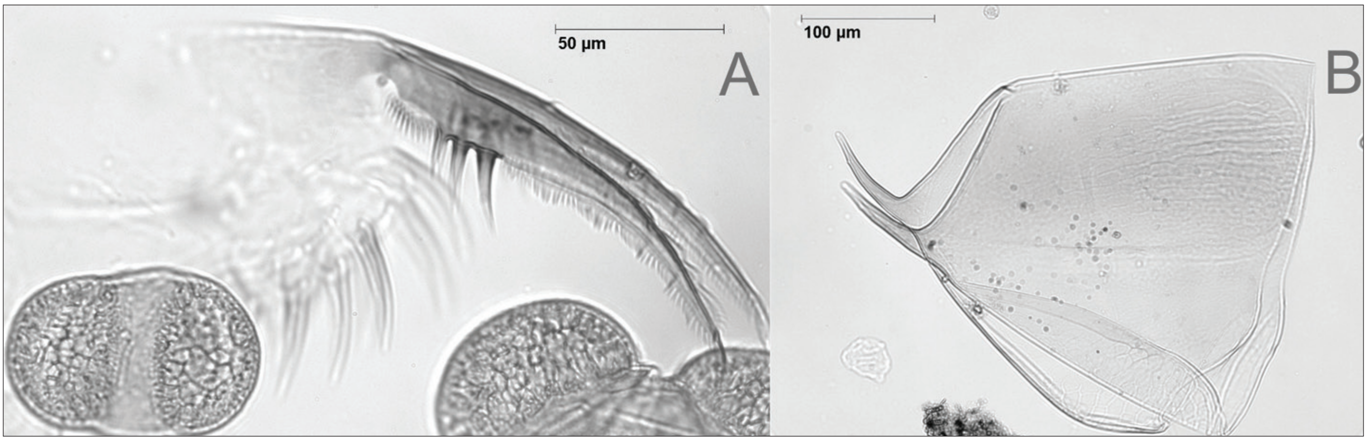

Figure 1: Micrographs of fossil water flea body parts. ***A****)* Daphnia *post-abdominal claw, with two pine pollen grains.* ***B****)* Bosmina *carapace (Photographs: A. DeSellas).*

of measured Ca declines pre-date the longest environmental records in North America (Likens et al., 1996). Therefore, we must employ indirect methods to address questions regarding the onset and extent of Ca decline. One such approach is geochemical modeling, with predictions suggesting that an acid-induced release of Ca from watershed soils has led to artificially elevated lakewater Ca levels, and that current declines are a return from this elevated state (Watmough and Aherne, 2008). However, questions remain, including how current Ca levels compare to historical levels, what minimum levels will eventually be reached, and what will be the ecological implications of falling Ca concentrations? These are all questions that are well suited to paleolimnological investigations, provided that an appropriate indicator is available.

Recent methodological developments

The crustacean zooplankton, especially many cladoceran taxa (water fleas), have long been studied in an acidification context, but several of their features also make them important paleoindicators of environmental Ca decline. They leave exoskeletal remains that preserve well in lake sediments (Fig. 1), and their survival depends on lakewater Ca levels above taxon-specific survival thresholds, given a life strategy of repeated molts and subsequent regeneration of a Ca-rich exoskeleton (Alstad et al., 1999). There is clear differentiation in the Ca requirements of different cladoceran taxa, with differences of up to 20-fold in the Ca content among crustacean zooplankton species. In particular, Ca-rich daphniids have much higher needs than non-daphniid crustacean species such as bosminids, *Holopedium* and calanoid and cyclopoid copepods (Waervagen et al., 2002; Jeziorski and Yan, 2006). Recent syntheses of laboratory and field work have identified that a Ca concentration of 1.5 mg/L acts as a performance threshold for the most common crustacean zooplankton found in Canadian Shield lakes (*Daphnia pulex*; Ashforth and Yan, 2008; Cairns and Yan, 2009), where many water bodies are nearing (or have already crossed) this threshold value (Jeziorski et al., 2008a). An initial attempt to use the differences in Ca content in daphniid resting eggs (ephippia) as the basis for a paleoindicator of Ca change failed (Jeziorski et al., 2008b), apparently because of the previously unknown capacity of daphniids to withdraw Ca from ephippia. Instead, more conventional assemblage approaches are required and have proved to be more successful, as described below (Jeziorski et al., 2008a).

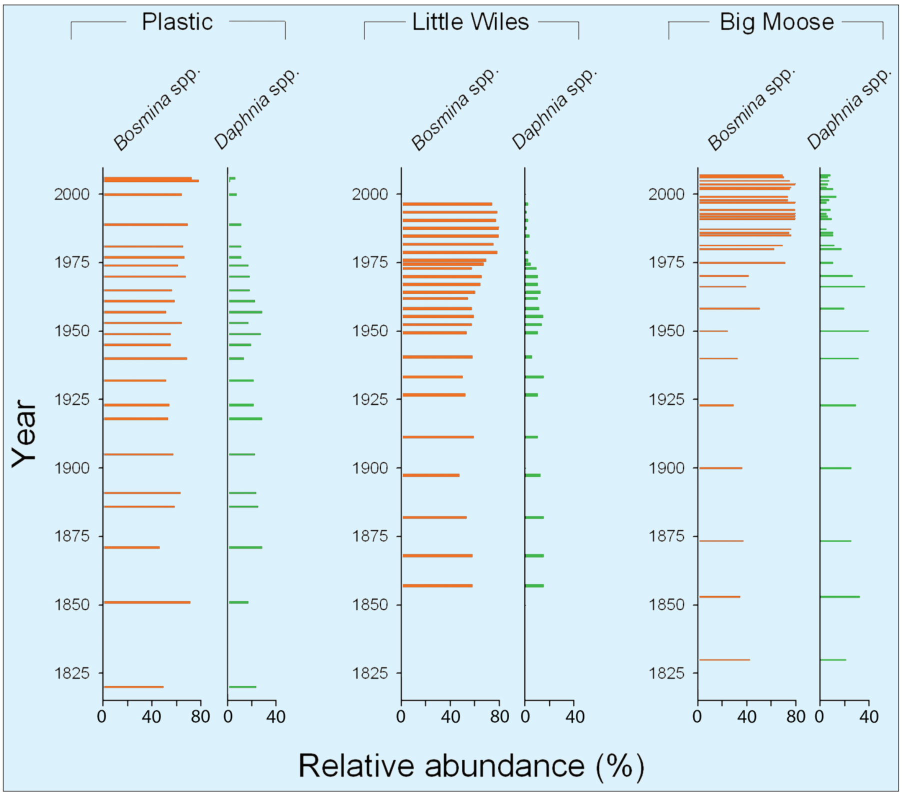

*Figure 2: Sedimentary profiles of changes in the relative abundance of crustacean zooplankton remains for three softwater lakes in eastern North America (Plastic Lake, Ontario, Canada; Little Wiles Lake, Nova Scotia, Canada; Big Moose Lake, New York, USA). Similar trends of declining sedimentary abundances of Ca-rich daphniids (****green****) relative to Ca-poor bosminids (****orange****) are common across all three regions (from Jeziorski et al., 2008a. Reprinted with permission from AAAS).*

Findings to date

Recent investigations of softwater lakes that are nearing or have recently fallen below the 1.5 mg/L threshold in eastern North America have recorded declines in the relative abundance of Ca-rich daphniid sedimentary remains (post-abdominal claws; Fig. 1A) in dated sediment cores, relative to other preserved crustacean zooplankton (Fig. 2; Jeziorski et al., 2008a). These declines could not be readily attributed to changes in chemical variables other than reduced Ca availability, because other changes over this time period should have favored larger Ca-rich daphniid species over their smaller Ca-poor competitors. This trend of a relative decrease in daphniid remains since preindustrial times was also recorded in lakes with current Ca concentrations up to 2.0

mg/L (Jeziorski et al., 2008a), suggesting that the threshold measured under natural conditions may actually be higher than the 1.5 mg/L threshold identified in laboratory studies. The number of lakes at or nearing this threshold is considerable and increasing; an examination of changes in Ca concentrations for a set of 770 lakes covering a broad geographical area in Ontario (Canada) found that 35% of lakes currently have <1.5 mg/L of Ca, while 62% are already below 2.0 mg/L, reflecting substantial increases in percentages since the 1980s (Jeziorski et al., 2008a).

Future research avenues

We are continuing to examine the use of crustacean zooplankton as indicators of past Ca conditions across a wide spectrum of Canadian Shield lakes. For example, to better interpret changes observed in sediment profiles, more information is required regarding specific laboratory-determined Ca thresholds for taxa other than *Daphnia pulex* to further refine our current separation of taxa into Ca-rich vs. Ca-poor categories. Additionally, further examinations of the potential indirect impacts of Ca decline are warranted, such as the differential uptake of Ca and Sr, and/or isotopic differences as Ca concentrations fall (Peters et al., 2008). Finally, Ca decline has been largely attributed to either acid deposition, biomass harvesting or some combination of both, yet similar declines have been observed in regions where the effects of these stressors have been minimal, and so other environmental changes, such as decreases in atmospheric deposition of particulate dust (Hedin et al., 1994) may also be contributing to the observed Ca declines. Given our limited current understanding of both the biological consequences of reduced Ca availability, as well as its geographic extent, further investigations are clearly warranted.

Note

The term "aquatic osteoporosis" was coined by M. Turner, a co-author on Jeziorski et al., 2008a.

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Calibration-in-time: Transforming biogeochemical lake sediment proxies into quantitative climate variables

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Lake sediment records are underrepresented in comprehensive quantitative high-resolution (annual, sub-decadal) multi-proxy climate reconstructions for the past 1 ka due, in part, to the problems associated with calibration of biogeochemical lake sediment proxies. Here we present a case study and highlight five methodological issues that are important to establish quantitative paleoclimate records from biogeochemical proxies in non-varved lake sediments.

Comprehensive quantitative annually resolved multi-proxy climate reconstructions for the past ca. 1 ka are arguably among the most spectacular and widely recognized highlights of current paleoclimate research (see PAGES Focus 2: Regional Climate Dynamics). In this context, lake sediment archives are surprisingly underrepresented in the data series used for such purposes. Indeed, the number of well-calibrated long time series of quantitatively reconstructed climate variables at (near) annual resolution derived from lake sediments is limited; most of the reconstructions are descriptive, and samples have variable temporal resolution or are discontinuous; with the exception of the few annually laminated lake sediments.

In contrast to biota-based transfer functions (e.g., diatoms, pollen, chironomids; e.g., Birks, 1998), bio-geochemical sediment proxies can be transformed into quantitative climate variables only through a calibration-in-time approach: a time series of sediment proxies regressed against a series of meteorological observations.

Recently, we started to explore possibilities to produce millennial-long, highly resolved (near-annual) quantitative climate reconstructions from biogeochemical data using a calibration-in-time approach in non-varved lake sediments (von Gunten et al., 2009a). The question was "can a methodology be developed to produce time series of adequate quality for regional climate reconstructions?" Yes, and the result is shown in Figure 2.

The statistical procedure per se is known from tree-ring research (e.g., Cook et al., 1994; Esper et al., 2005) and has been applied in quantitative climate reconstructions from annually laminated lake sediments (e.g., Trachsel et al., 2008). But would a calibration-in-time also work in non-varved sediments? Evidently, two things are needed: a) an extremely accurate high-resolution sediment chronology with smallest uncertainties for the calibration period (which typically covers ca. 100 years; von Gunten et al., 2009b; Fig. 1); and b) sediments corresponding to the calibration period must be sampled at highest possible resolution (e.g., near-annual; von Gunten et al., 2009a; Fig. 2). We consider the following five methodological issues to be highly critical for the success of this approach:

1) Rigorous testing of calibration chronology

While radiometric techniques (mostly ^{210}Pb) are widely used to date young sediments, little attention is paid to the choice and evaluation of the numerical model used to convert activity profiles into sediment ages. Although well documented (e.g., Appleby, 2008), it is often ignored that the three established models (Constant Flux Constant Sedimentation, CFCS; Constant Initial Concentration, CIC; Constant Rate of Supply, CRS) may yield very different chronologies for the same profile (Fig. 1A). A fourth model, the inductive Sediment Isotope Tomography (SIT) model is poorly established in the paleolimnological literature. SIT uses a forward modeling approach and calculates, in contrast to CIC and CRS, sediment ages without a-priori model assumptions (Carroll and Lerche, 2003). Our systematic comparison of all the models in two different lakes in Chile (Fig. 1; von Gunten et al., 2009b) shows

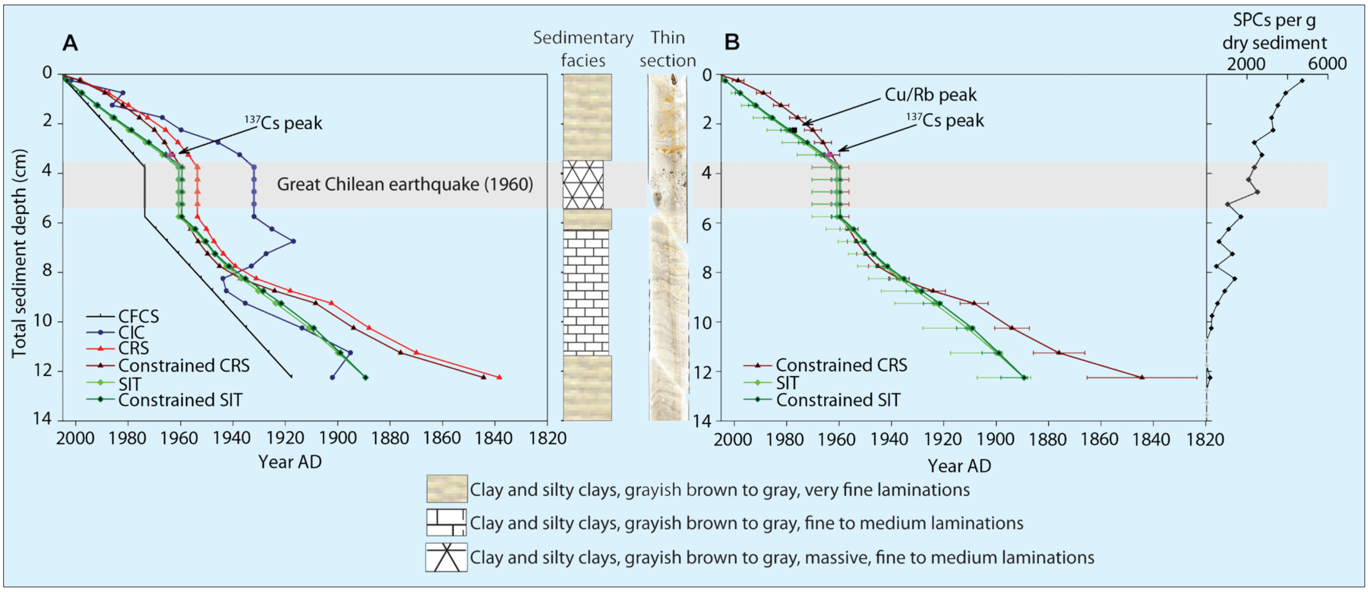

*Figure 1: Calibration chronologies for Laguna El Ocho, central Chile (von Gunten et al., 2009b). **A**) Different results obtained for the six chronological models applied; the dating uncertainty is not shown here. The turbidite between 4 – 5.5 cm sediment depth (gray bar) is related to the 1960 earthquake. **B**) The two most plausible chronologies; the SIT model (green line) has been verified (CRS model falsified) with a documented (AD 1977) Cu emissions peak of a nearby Cu mine (expressed as Cu/Rb ratio), the ^{137}Cs peak AD 1964, the 1960 earthquake and the Spheriodal Carbonaceous Particles (SCPs) profile for the lower part of the chronology (large smelter installed AD 1909).*

that the SIT model yields the best results compared with independent chronostratigraphic markers of known age. Indeed, testing against such markers (e.g., flood markers, tephra layers, seismites, Spheroidal Carbonaceous Particle (SCP) profiles) provides an objective choice for the selection of the "best" ^{210}Pb chronology (and rejection of the others).

Conclusion 1:

We recommend routine calculation and comparison of chronologies from all three standard models (CIC, CRS and SIT), tests of robustness and verification against independent markers (available in most cases) to identify the best chronology.

2) Reducing uncertainty in the chronology

All sediment ages are probabilistic. Typically, the standard deviation increases with increasing depth or age. It is the standard deviation of the chronology during the calibration period (i.e., last 100 years) that is critically important for calibration–in–time. The time series of proxy data needs to be smoothed to account for dating uncertainties before a regression with meteorological data is possible (Koinig et al., 2002). Consequently, the standard deviation in the chronology determines the degree of smoothing needed and, finally, the maximum possible resolution of the climate reconstruction (or the loss of the high-frequency component of climate variability). The software of the SIT model (Carroll and Lerche, 2003) allows the numerical assimilation of ^{210}Pb-independent discrete chronostratigraphic markers (forcing the forward modeling through a specific age/depth point), while reducing the standard error of the continuous model chronology. This is of significant advantage for calibration-in-time, in particular for the early instrumental period when dating errors are typically high.

Conclusion 2:

Independent stratigraphic markers are worth the extra effort and are important to reduce the standard deviation of the chronology in the calibration period. This has direct consequences for the quality of the calibration and for the maximum temporal resolution of the reconstruction and, ultimately, for the preservation of the high-frequency signal in the paleoclimate variability.

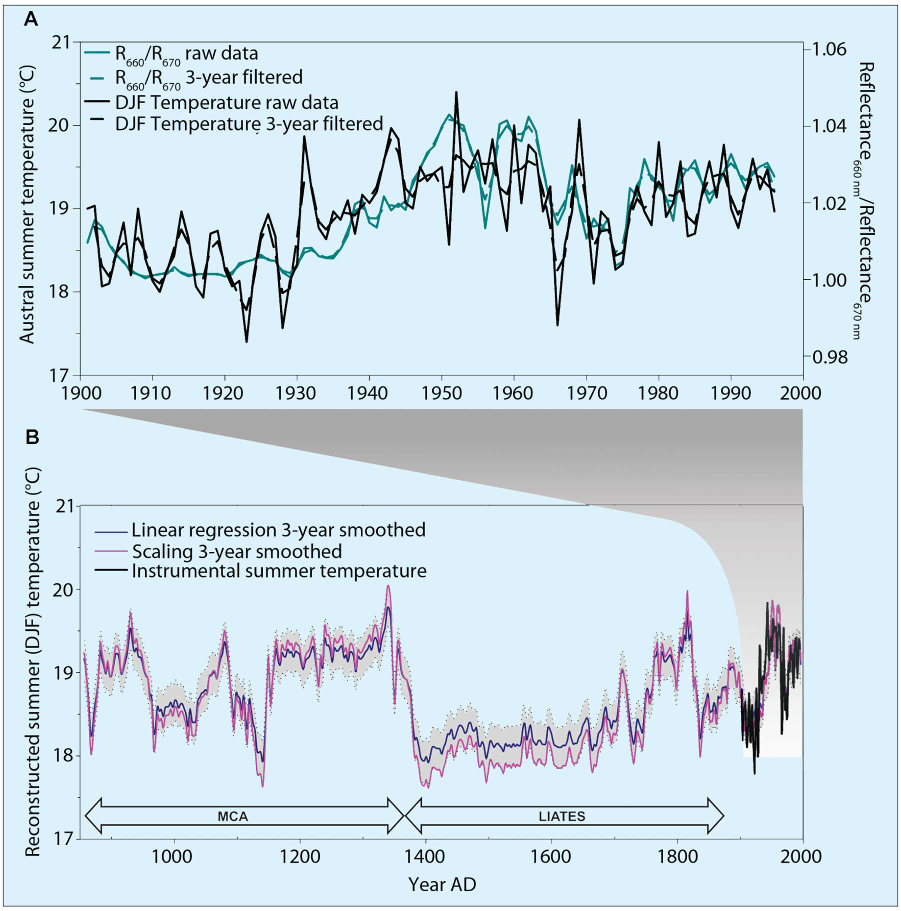

*Figure 2: **A**) Calibration-in-time and calibration statistics for raw data and 3-year filtered data of Laguna Aculeo, central Chile; we used the reflectance ratio R660nm/R670nm (non-destructive in-situ high-resolution reflectance spectroscopy) as a proxy for austral summer temperature. Loss of the inter-annual climate variability in the sediments (blue line compared with black line) is likely due to bioturbation. **B**) Instrumental DJF temperatures and the reconstruction back to AD 850 (3-year resolution). MCA = Medieval Climate Anomoly, LIATES = Little Ice Age Type Events. Here we used the ratio Reflectance 660nm / Reflectance 670nm as a proxy for the photopigments chlorin, which is significantly correlated (p < 0.01) with austral summer temperature. For details see von Gunten et al., 2009a.*

3) The significance of sampling, sampling resolution

This issue has two aspects: a) sediments are sampled to establish the (^{210}Pb) chronology. Stratigraphic sampling according to sedimentary microfacies substantially improves the quality of ^{210}Pb chronologies (Arnaud et al., 2002). Layers with rapid sedimentation (e.g., turbidites) need to be excluded; and b) samples for the analysis of the lake sediment proxies must be taken continuously and, ideally, at annual resolution, at least throughout the calibration period. This is the basic requirement to target e.g., sub-decadal climate variability (such as ENSO cycles).

Therefore, the sediment core that is used to establish the proxy data must not be cut before the chronology for the calibration period is fully established, and sampling intervals along the sediment core should be adjusted according to local sedimentation rates. Furthermore, the core used to establish the chronology and the one used to produce the proxy data series must have a perfect micro-stratigraphic match at the millimeter-scale. In practice, this is only possible on two halves of one split core, or on varved sediments. In this context, the advantage of using non-destructive methods (XRF scanning or in-situ reflectance spectroscopy scanning (Kalugin et al., 2007; Rein and Sirocko, 2002; von Gunten et al., 2009a; Fig. 2)) is obvious.

Conclusion 3:

Establish the chronology of the calibration period first, and sample the sediments for the proxy analyses afterwards (according to the chronology).

4) Sampling resolution, analysis of the meteorological data

Ultra fine "technical" sampling resolution does not necessarily correspond to the "true" resolution of (climate) variability recorded in the sediments. For a number of reasons (dating and sampling errors, synchronizing of proxy data points to a calendar scale with homogenous temporal resolution) raw proxy series must be filtered. As a rule of thumb, the resolution of the raw data series should be 3-4 times higher than the final resolution (highest frequency band of climate variability) envisaged. System-inherent filters, such as bioturbation may destroy the highest true (or meaningful) temporal resolution of climate variability that is potentially recorded in a lake. Thus, this type of research should actually start with the statistical analysis of the local meteorological time series, and calculate the sampling resolution that is required to detect the dominant features of variability, trends and extremes of the local climate.

Conclusion 4:

The "technical" and the "true" sampling resolution, and the "envisaged" (best possible) temporal resolution of the climate reconstruction have their restrictions. These must be carefully assessed.

5) The properties of the calibration period

Obviously, all the caveats for regression-based reconstructions also apply to a calibration-in-time (e.g., non-modern analogues, long-term trends). Furthermore, the length of the instrumental meteorological time series is often limited. Moreover, many of the calibration parameters (starting and ending point, data homogenization, selection of the split periods for cross validation, etc.) are an optimization process and an expert choice. Instead of using split periods, it might be justified to use the entire meteorological data series for a proper calibration. In addition, the use of reanalysis data sets should be considered and tested (e.g., ICOADS http://www.cdc.noaa.gov/data/ or ACRE http://www.met-acre.org/) in areas where instrumental series are very short. Shorter calibration periods often exhibit pronounced (warming) trends, which is a problem for the calibration statistics.

Conclusion 5:

The choice of the appropriate calibration (period and parameters) is not a priori known. A novel approach would be to produce probabilistic reconstructions based on an ensemble of different calibrations.

Conclusions and outlook

New developments in scanning techniques have boosted the acquisition of high-resolution biogeochemical proxies from lake sediments. Faced with the challenges mentioned above, these data must be converted into quantitative climate (environmental) variables using calibration-in-time. We have shown here that this task can be accomplished; yet, it requires careful consideration and planning of the practical work, further refining of the methodology (as proposed above), as well as systematic exploration of the potentials and limits of the individual methods used.

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Environmental and climatic changes inferred from lake deposits in China: A review of recent progress

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In recent years, Chinese paleoscience including paleolimnology has made huge progress, providing a wealth of data on past environmental and climatic change on various timescales. A brief review is presented here on recent research based on Chinese lake sediment records and their significance in the PAGES context.

Climate records in the arid areas of northwestern China

A large share of paleolimnological research in China has focused on climate records from lakes located in the vast arid and semi-arid areas of northern and western China, which include the regions of Inner Mongolia, Xinjiang, Qinghai and Tibet. These climate records are concerned with changes in precipitation or effective moisture. Most of these lakes are brackish or saline and often very shallow (Fig. 1A). The most commonly used proxies are pollen, stables isotopes ($\delta^{13}C$, $\delta^{18}O$), ostracods, grain size and various geochemical variables. Because of bad preservation in these saline, highly alkaline and shallow lakes, biological proxies, such as diatoms,

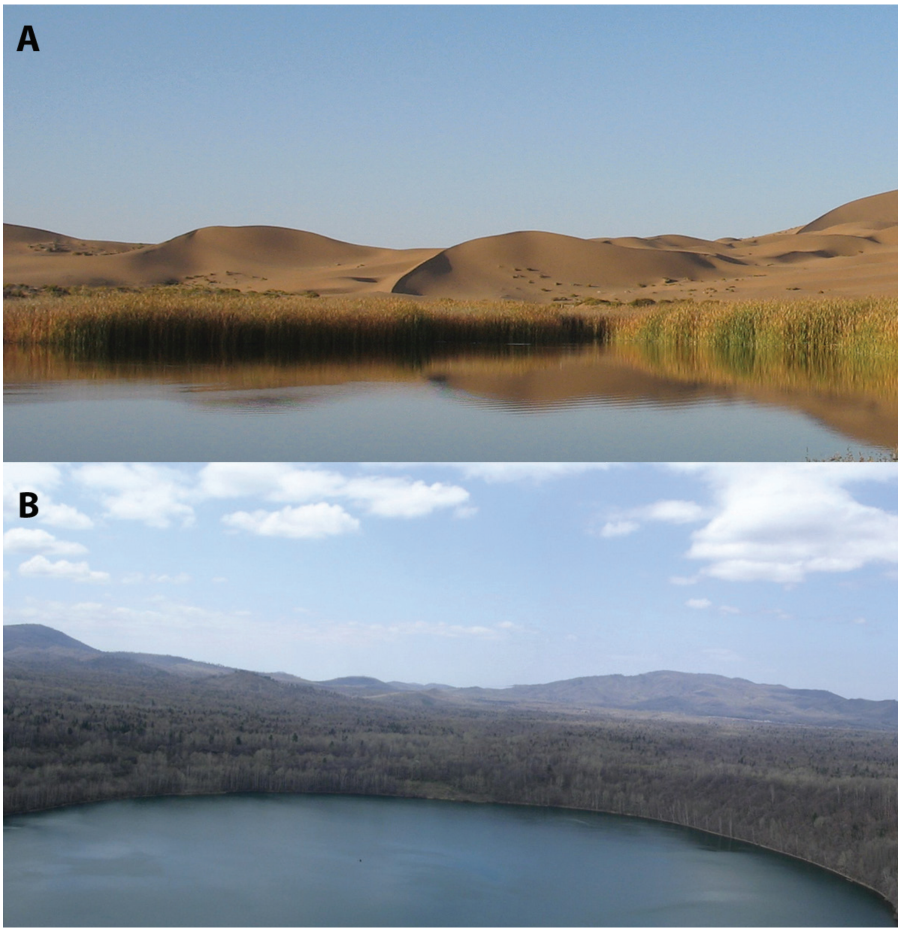

Figure 1: Contrasting lakes from China. ***A****) A shallow, brackish lake from the Badan Jilin desert in Inner Mongolia,* ***B****) Sihailongwan Lake, a deep maar lake in northeastern China.*

can seldom be used on long sediment sequences. In the most recent review on this topic, Chen et al. (2008) used a selection of the most reliably dated lake sediment records from northern China to summarize the changes in moisture during the Holocene. They found that in arid China the early Holocene was characterized by dry conditions, the mid-Holocene was less dry whereas the late Holocene was moderately wet. A similar pattern is reported from north central China (Xiao et al., 2004; 2008). Therefore, the Holocene moisture history in arid China appears to be out-of-phase with that of areas located further south and east, which are under the influence of the Asian summer monsoon. As shown by many paleoclimate records, such as the pollen records from southern China (Shen et al., 2006; Wang et al., 2007) and the stalagmite records of central and southeastern China (Wang et al., 2005; Cosford et al., 2008), a humid climate characterized the early Holocene in monsoonal China, whereas drier climates prevailed during the late Holocene. These changes were driven by variations in low-latitude summer insolation. By contrast, the changes observed in the lake records of arid China appear correlated with North-Atlantic sea-surface temperatures, which indicate an atmospheric teleconnection via the Westerlies.

Lake Qinghai

Lake Qinghai, located on the northeastern margin of the Tibetan Plateau, is of particular interest for paleoclimate research because of its large size (the largest saline lake in China, covering 4400 km^2) and its location at the junction of influence from three major climate/atmospheric pressure systems: the East Asian and Indian summer monsoon systems and the Westerlies coming from Eurasia. A comprehensive review of paleolimnological research carried out on Lake Qinghai was completed by Colman et al. (2007) with the aim of collecting background information before analyzing the long sediment record retrieved in 2005 by the International Continental Drilling Program (ICDP). The sediment infill at the lake bottom is over 700 m thick (An et al., 2006) and therefore may archive the dynamics of the Asian monsoon systems, as well as the tectonic history of the Tibetan Plateau over the last eight millions years. On a much shorter timescale, novel analytical approaches have been used to study Lake Qinghai Holocene history. For example, alkenones were used for the quantitative reconstruction of temperature and salinity over the past 2 ka (Liu et al., 2006), whereas analysis of bacteriophaeophytin pigment abundance yielded past blooms of anaerobic phototrophic bacteria as a proxy for solar and monsoonal activities over the past 18 ka (Ji et al., 2009).

Paleolimnology in maar and crater lakes

Among the lacustrine records, those from crater and maar lakes are often considered to be especially well suited for paleoenvironmental studies because volcanic lakes are generally small and simple systems (in terms of hydrology and morphology) that appear to be more favorable for the evaluation of paleolimnological records than large and complex lakes (Baier et al., 2004). Starting in the late 1990s, a collaborative project between Chinese and German scientists aimed at studying the numerous Chinese maar lakes for paleoclimatic reconstructions (see Liu et al., in *PAGES news*, July 2001).

In southern China, the Huguang maar lake sediment record has been intensively studied. Yancheva et al. (2007) have used sediment Titanium content and magnetic properties as proxies for reconstructing the intensity of the winter monsoon, which consists of dry and cold winds that transport dust particles from the deserts of northern China. The fossil diatom record of Huguang maar lake was analyzed by Wang et al. (2008) (Fig. 2). Sediment trap experiments in the modern lake revealed that the seasonal distribution of the dominant planktonic species, *Cyclotella stelligera* and *Aulacoseira granulata*, is controlled by wind-driven turbulence in the water column. During the late Glacial and the Holocene, the same two diatom taxa dominated alternatively in the sediment record. These shifts seem to support Yancheva et al's (2007) interpretation of Ti abundance as a proxy for the winter monsoon winds. However, their assumption that the winter and summer monsoons were anti-correlated on a decadal scale is not supported by historical documents (Zhang and Lu, 2007).

In northeastern China, several maar lakes have been investigated and the presence of annual laminations (varves) in the sediment has been established (Chu et al., 2005; 2008; 2009; You et al., 2008). As the sediment sequences are almost continuously laminated, very robust chronologies could be constructed by varve counting combined with AMS ^{14}C dating. In Lake Sihailongwan (Fig. 1B), the upper 25 m of the sediment sequence comprise the last 65 ka (Mingram et al., 2007). In this lake, paleolimnological research is well advanced, especially over two time windows: a) the late Glacial and early Holocene for which geochemical (Schettler et al., 2006a; Parplies et al., 2008) and pollen investigations have been completed (Stebich et al., 2009), and b) the late Holocene with geochemical (Schettler et al., 2006b) and minerogenic analyses (Chu et al., 2009). For the late Glacial in particular, short cold/dry spells were recorded that are perfectly correlated with events reported from the Greenland ice core records. Such synchronicity in abrupt climate shifts demonstrates that the North Atlantic and East Asian regions were strongly coupled via atmospheric teleconnections. The varve-based chronologies that have been established from several lakes also enabled precise determination of the age of several tephra layers preserved in the sediment records, thereby providing a much improved chronology of volcanic eruptions in northeastern China (Liu et al., 2009).

Outlook

In addition to the research topics outlined above, lake sediment records are also used to investigate the history of eutrophication, especially in the large and shallow floodplain lakes of the middle and lower reaches of the Yangtze River, which is one of the most densely populated and industrialized areas in China. Paleolimnological research on these lakes mainly relies upon diatom-based reconstructions of total phosphorus concentrations in lake water (Yang et al., 2008; Dong et al., 2008). The multi-proxy record from Lake Erhai in Yunnan, southern China, is also an excellent example of how to use lake sediment records to reconstruct climate-human-environment interactions during the Holocene (Dearing et al., 2008).

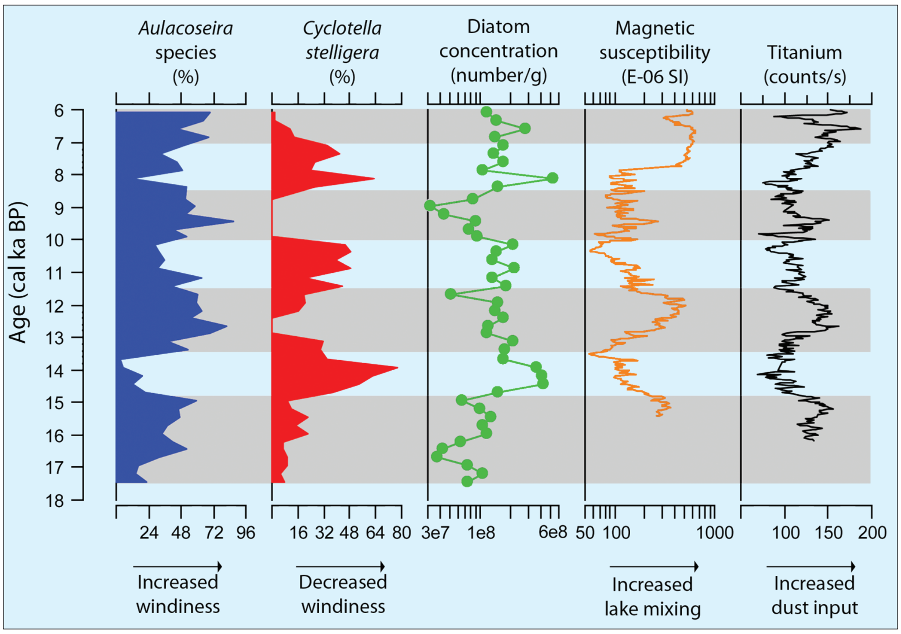

Figure 2: Comparison of the diatom data; % abundances of the planktonic centric taxa Aulacoseira *spp. (**blue**) and* Cyclotella stelligera *(**red**), as well as diatom concentration (**green**) (Wang et al., 2008), with the titanium (Ti) content (**black**) and magnetic susceptibility records (**orange**) (Yancheva et al., 2007) from the Huguang maar lake (South China). High abundances of* Aulacoseira *spp. are indicative of periods of turbulent water column mixing due to strong winds, while increased abundance of* C. stelligera *suggests thermally stratified, weak wind conditions. The seasonal change in relative abundance of these taxa can, therefore, be used as a proxy of the strength of winter monsoon winds. Ti and magnetic susceptibility are proxies for dust input and lake mixing, respectively.*

Acknowledgements

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Paleolimnology of African lakes: Beyond the exploration phase

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Longstanding research questions on tropical climate-human-ecosystem interactions can be tackled by combining novel and traditional paleoenvironmental proxies from high-quality sediment archives in African lakes.

Paleolimnology of African lakes: Something particular

African lakes have had a special allure to paleolimnologists ever since pioneering work by Dan Livingstone and his students revealed their potential for tropical paleoecology and paleoclimatology. However, it took time before their particularities (e.g., methane-charged muds, unstable sedimentary environments associated with fluctuating lake level) and logistical challenges no longer hampered application of the modern paleolimnological techniques that were developed in Europe and North America during the 1980s. Given the scarcity of annually resolved African lake records, progress in African paleolimnology depends on well-constrained radiometric chronologies. This is often challenging, because lakes with the hydrological sensitivity required to register decade- to century-scale climate variability tend to display significant variability in sedimentation rates and radiocarbon reservoir age, with complicating effects on the age-depth relationship that cannot easily be resolved by $^{210}Pb/^{14}C$-based age models. As for the reconstructions themselves, the principal issues are that, firstly, past human impacts on African lakes and the surrounding landscapes cannot be determined without accounting for major climatic influence on ecosystem dynamics at all timescales; and secondly, the pressing need for quantitative temperature proxies, and for hydrological proxies unaffected by lake-groundwater interactions and temperature effects on evaporation. Basin-specific hydrological modeling is one solution, exemplified by work on Rift Valley lakes in Ethiopia (Legesse et al., 2004) and Kenya (Bergner et al., 2003; Duhnforth et al., 2006). Other methodological advances have come from the development of regional calibration datasets that constrain the ecological indicator value of in-lake biological proxies (e.g., Rumes et al., 2005; Eggermont et al., 2006; 2009), and application of new organic biomarker proxies for temperature and moisture balance to African lake records.

Resolving African climate history

Reconstructions of African climate history using these improved techniques testify to the global teleconnection of climate variability at glacial-interglacial, orbital and shorter time scales but also reveal distinct tropical climate processes. For example, results of ICDP-sponsored drilling in Lake Malawi (southeastern tropical Africa) and Lake Bosumtwi (tropical West Africa) show that tropical African climate history differs from the characteristic 100-ka saw-tooth pattern of continental ice-sheet growth and decay. Most importantly, tropical aridity during the Last Glacial Maximum (MIS2) paled in comparison with mega-droughts recurring at ~21-ka intervals during MIS5 and MIS4, when high eccentricity strengthened precessional insolation forcing (Scholz et al., 2007; Cohen et al., 2007). Penetrating a sub-lacustrine ridge in Lake Tanganyika with Kullenberg-coring methods, Felton et al. (2007) recovered a continuous climate record back to the base of MIS3. Analyses of organic biomarker proxies for past temperature (the TEX_{86} index of crenarchaeotal membrane lipids) and moisture balance (the δD of leaf waxes) by Tierney et al. (2008) revealed that millennial MIS3 drought episodes in southeastern tropical Africa coincide with Heinrich events (Fig. 1), suggesting northern high-latitude influence on sea-surface temperature in the western Indian Ocean. This study also confirmed the result of Powers et al. (2005) from Lake Malawi, which showed that postglacial warming started ~20 ka BP, i.e., coincident with the start of major continental ice-sheet melting, but well before the rise in atmospheric CO_2. A moisture balance reconstruction from Lake Malawi based on the C3/C4 vegetation ratio incorporated in the $\delta^{13}C$ of leaf wax alkanes (Castañeda et al., 2007) supports evidence for early Holocene drought in southern tropical Africa (Nash et al., 2006; Garcin et al., 2007), associated with the rapid resumption of Intertropical Convergence Zone (ITCZ) migration far into the Northern Hemisphere at the end of the Younger Dryas (Talbot et al., 2007). Reviewing all relevant lake (and nearshore marine) paleoclimate records/patterns across southern Africa, Gasse et al. (2008) report progress in resolving the longstanding conflict between evidence for a dry LGM (and Younger Dryas) in Lake Malawi (e.g., Johnson et al., 2002) vs. wet conditions during those times recorded in nearby Lake Masoko (Garcin et al., 2006). Another issue of longstanding debate has been whether Holocene retreat of the northernmost summer-time position of the ITCZ caused a gradual or abrupt mid-Holocene weakening of the West African monsoon over North Africa, and thus a gradual or abrupt mid-Holocene desiccation of the Sahara desert. Multiple-proxy analyses on the uniquely continuous sediment record of a groundwater-fed lake in northern Chad (Kröpelin et al., 2008) revealed that, while the aquatic ecosystem responded to deteriorating moisture balance with a threshold response to hydrological closure of the lake basin, the surrounding terrestrial ecosystem evolved gradually from a grass savannah to Sahelian scrubland to hyper-arid desert, between 5.6 and 2.7 ka.

Until recently, reconstructions of Holocene climate history in sub-Saharan Africa showed affinity with either Northern or Southern Hemisphere summer insolation forcing. A new 25-ka lake record from Lake Challa near Mt. Kilimanjaro, just south of the equator in East Africa, promises to reveal the history of hydrological change in the western Indian Ocean domain, where latitudinal ITCZ migration far north and south of the equator generates a markedly bimodal pattern of seasonal rainfall (Verschuren et al., ESF EuroCLIMATE project CHALLACEA). However, because the north-south trending Congo Air Boundary, where moisture from the Atlantic and Indian Ocean meet, is situated near ~33-35°E above the East African plateau, the climate history of much of tropical Africa bears a strong signature of variation in Atlantic Ocean circulation. This is particularly evident during the main phase of the Little Ice Age (LIA; 1400-1750 AD), when drought in western tropical Africa (Shanahan et al., 2009) and central equatorial Africa including western portions of the East African plateau (e.g, Russell and Johnson, 2007) contrasted with above-average rainfall over the eastern half of the plateau (Verschuren et al. 2000a). Lake Victoria

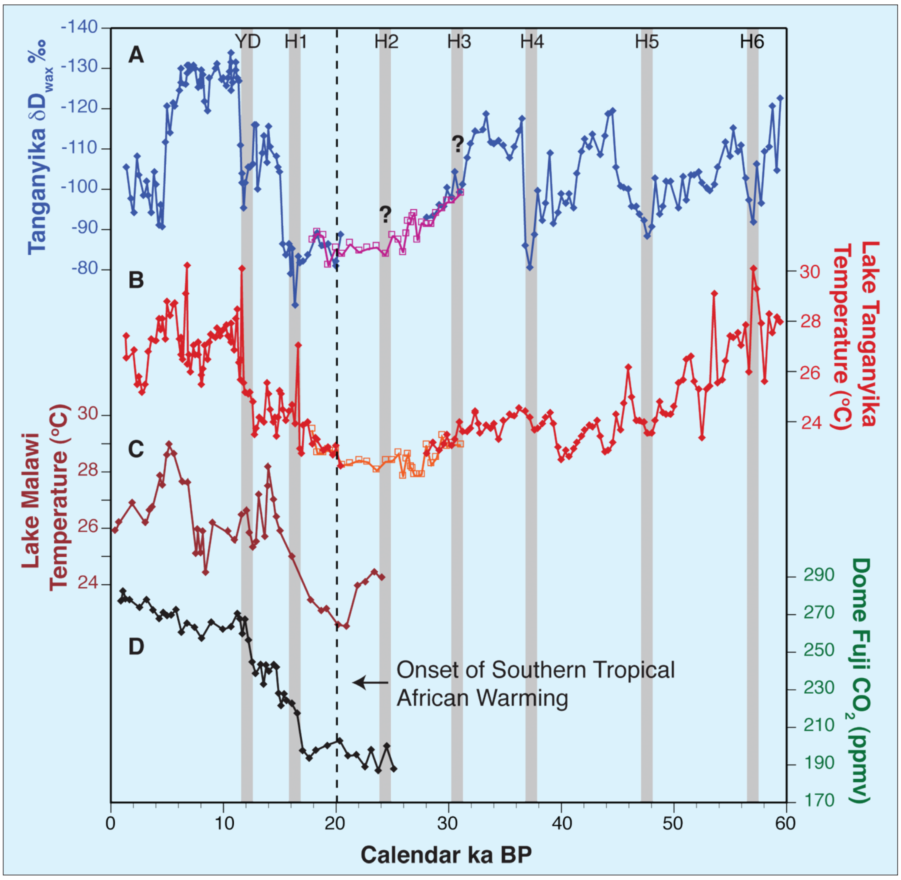

*Figure 1: Comparison of Lake Tanganyika $\delta D_{leaf\ wax}$-inferred regional moisture balance (**A**; blue and purple lines) and TEX_{86}-inferred temperature (**B**; red and orange lines) with the Lake Malawi TEX_{86}-inferred temperature (**C**; brown line; Powers et al., 2005), and glacial-to-Holocene record of atmospheric CO_2 in Dome Fuji ice (**D**; black line; Kawamura et al., 2007). Gray bars indicate the Younger Dryas (YD) and Heinrich events H1 to H6; H2 and H3 are not apparent in Tanganyika basin hydrology. Figure modified after Tierney et al. (2008).*

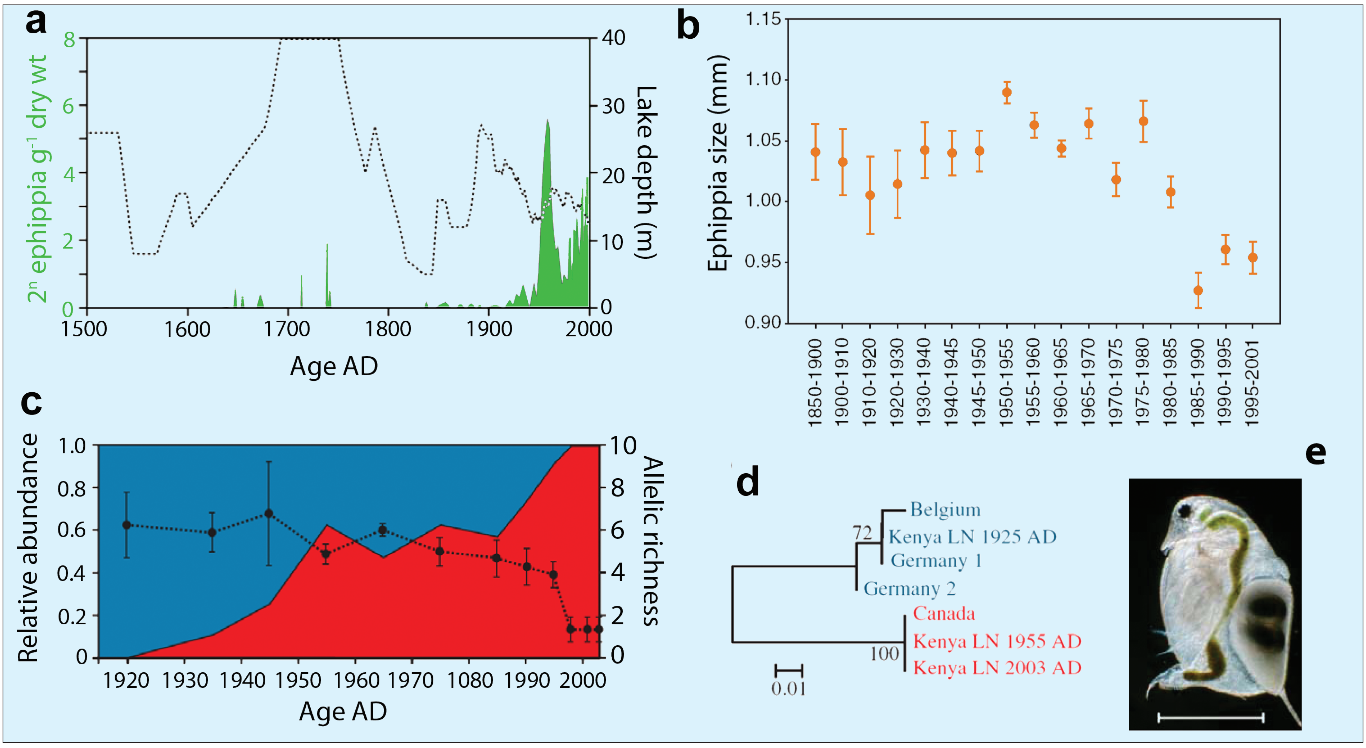

Figure 2: History of the water flea Daphnia pulex *population in Lake Naivasha (Kenya) reconstructed from the sediment record of its fossil resting eggs (ephippia).* ***a****) Population abundance through time (green area) in relation to historical lake-level fluctuations (dotted line), showing the relative scarcity of this species prior to the 1940s. 2^n = ephippia abundance on base 2 logarithmic scale.* ***b****) Evolution of mean water-flea body size since the mid-19th century derived from measurements of fossil ephippia. This indicates i) lowered size-selective fish predation in the 1950s due to fishery collapse associated with the mid-20th-century lowstand, and ii) recently increasing fish predation attributed to the disappearance of submerged aquatic macrophytes, which has resulted from anthropogenic siltation and eutrophication.* ***c****) Relative abundance of the asexual American genotype (red) and the indigenous African genotypes (blue) of* D. pulex *in Lake Naivasha since the inadvertent introduction of the American* D. pulex *variant during a fish-stocking effort in the 1920s, based on genetic analysis of multiple individual fossil ephippia in each sediment level; also shown is the associated loss in the local population's genetic diversity through time (allelic richness: dotted line with 95% confidence intervals).* ***d****) Phylogenetic tree based on a mitochondrial gene fragment showing the relationship of Lake Naivasha* D. pulex *in 1925, 1955 and 2003 to populations from Belgium and Germany ('Old World' genotypes, including Africa) and Canada ('New World' genotypes). The scale bar indicates genetic distance, i.e., the number of base substitutions between the different gene variants (haplotypes).* ***e****)* D. pulex *with eggs visible inside the ephippium. The scale bar is 1 mm. Figures a, c and d are from Mergeay et al. (2006), b is from Mergeay et al. (2004).*

(Stager et al., 2005) and central Ethiopia (Lamb et al., 2007) display intermediate LIA rainfall anomalies, reminiscent of the regional patterns of modern ENSO teleconnections (Verschuren and Charman, 2008).

Resolving human impact on African ecosystems

Lake Tanganyika, buffered against the immediate impact of catchment disturbance by great depth and permanent stratification, produced the first paleolimnological evidence of African lake-ecosystem response to anthropogenic climate change (O'Reilly et al., 2003). This would be much harder to demonstrate in records from shallower African lakes, of which the aquatic communities show continuous species turnover due to habitat restructuring associated with lake-level and salinity fluctuations (Verschuren et al., 1999; 2000b). Paleolimnological studies on the population genetics of water fleas in such lakes show that their genotypic identity is stable through time as long as episodes of ecological crisis (such as lake desiccation) do not exceed the few decades during which resting eggs remain viable in bottom muds (Mergeay et al., 2007). Another paleogenetic study (Mergeay et al., 2006) revealed that an asexual American variant of the common water flea *Daphnia pulex*, introduced accidentally to Lake Naivasha in Kenya in the 1920s, has since outcompeted the indigenous, sexually reproducing variant of the same species not only locally, but throughout sub-Saharan Africa (Fig. 2).

Outlook of paleolimnology in African lakes

With the spatial patterns of past hydrological change across tropical Africa now better constrained, studies of climate-human-environment interactions can start to make rigorous distinction between climate-driven and anthropogenic impacts on the long-term dynamics of vegetation, fire and lake-water quality. Although today's profound landscape modification has mostly resulted from rapidly increasing demographic and agricultural pressure during the 20th century (Verschuren et al., 2002; Fleitmann et al., 2007), significant vegetation disturbance by indigenous agriculturalists extends to the late 18th century near Lake Tanganyika (Cohen et al., 2005), the 17th century in the Kenya highlands (Lamb et al., 2003), and at least the 10-11th century in western Uganda (Ssemmanda et al., 2005; Lejju, 2009; Russell et al., 2009). In western tropical Africa, landscape disturbance is thought to have started ~2400 BP when climate-induced drying opened up the rainforest for farming (Ngomanda et al., 2009). Future studies will paint an increasingly comprehensive picture of the timing and relative magnitude of indigenous human impact on the African landscape. Focusing on the highest-quality lake-sediment records and through innovative use of both traditional and novel proxies, African paleolimnology will no doubt continue to make significant contributions to our understanding of past tropical climate dynamics and climate-human-ecosystem interaction.

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South American lake paleo-records across the Pampean Region

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Paleolimnological studies of shallow lakes in the Pampean plains of South America provide detailed information on their response to both climate and anthropogenically-induced changes through time.

Study area and motivation

The lowland area east of the Andes stretches from Colombia and Venezuela in the North to the Argentinean Pampas in the South (approx. 40°S), and is a unique environment due to the development of a monsoon-like atmospheric pressure system (Vera et al., 2006). A mild climate dominates the more than 750,000 km^2 region, with a mean annual precipitation ranging between 600 and 1200 mm, making the soils appropriate for agriculture, cattle/sheep grazing and associated farming activities. The southernmost portion of this vast region is characterized by the fertile lowlands of the so-called "Pampas", including central to eastern Argentina, most of Uruguay, and the Rio Grande do Sul state in Brazil (Fig. 1a). The prevailing flat geomorphology of the area promotes the occurrence of shallow lakes that provide excellent paleoenvironmental archives. Recent investigations in South America have highlighted the advantage of studying past climate variability from a regional perspective (e.g., LOTRED-SA PAGES Working Group). This research was triggered to a large extent by early efforts led by the PAGES PEP-I initiative that resulted in a substantial increase of limnogeological studies in South America.

Calibrating the sedimentary record of recent climate changes

The 20th century in the Argentinean Pampa has been characterized by pronounced hydrological variability as evidenced by distinct lake level fluctuations, varying river discharges, and an extension of flooded lowlands (Fig. 1a and b). Piovano et al. (2002) have shown that the most recent sediments of Laguna Mar Chiquita (Fig. 1a) provide a unique sedimentological and geochemical record of these environmental changes. A stable isotopic model was generated, calibrated against instrumental data and further applied to older sediments (Piovano et al., 2004). This pioneer work using a limnogeological approach resulted in the development of the ongoing PALEO-PAMPAS initiative that aims to identify the role of the subtropical air masses during atmospheric circulation shifts beyond historical times (http://www.cicterra-conicet.gov.ar/english_areas-limno-programa.htm). As for the Laguna Mar Chiquita record, the main goal of this research is to now extend the reconstruction of past hydrological variability along a latitudinal transect in central Argentina (Fig. 1a). This reconstruction will be accomplished using sedimentological, geochemical and biological proxies in lacustrine sequences.

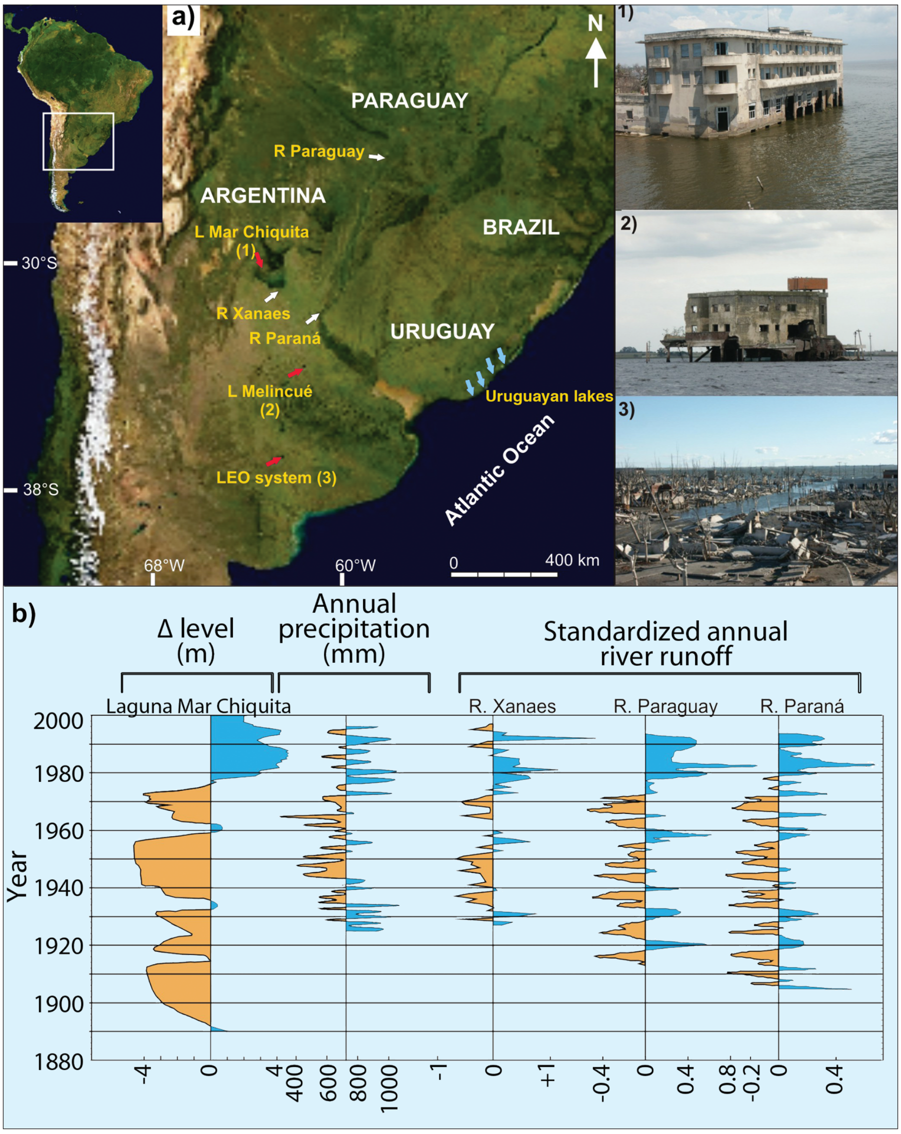

*Figure 1: **a**) Satellite image of study area (composite image created by NASA, public domain). White arrows indicate location of Xanaes River, Paraguay River and Paraná River gauging stations used in graphs of (b), red arrows indicate location of Pampas lakes (Mar Chiquita Lagoon, Melincué Lagoon and Lagunas Encadenadas del Oeste de Buenos Aires (LEO)), and blue arrows indicate location of Uruguayan lakes. Photographs on right illustrate the consequences of water-level increase: 1) Mar Chiquita Lagoon, 2) Melincué Lagoon, 3) Epecuén Lagoon in the LEO system. **b**) Comparison of instrumental lake level for Mar Chiquita Lagoon with an instrumental precipitation record and river runoff data. A lake level of 0 indicates an intermediate level that matches the AD 1977 shoreline (66.5 m asl). Positive values represent highstands (blue areas), and negative values indicate lowstands (brown areas). Annual precipitation in the Mar Chiquita lagoon basin covers AD 1925–96 interval. Values above average are in blue and below average in brown. Standardized runoff of Xanaes (within the Mar Chiquita lagoon basin), Paraguay, and Paraná Rivers with discharges above and below the mean annual runoff indicated in blue and brown, respectively (for further details see Piovano et al., 2004).*

Since the 1970s, hydroclimatic change has also been occurring at a sub-continental scale, covering the vast and productive region of southeastern South America (SESA) between 22°S and 40°S. Thus, it affects Uruguay, Paraguay, and subtropical regions of Argentina and Brazil. The close correspondence between the 20th century hydrological variability in both Pampean lakes and large-scale fluvial systems (e.g., Río Paraná; Río Paraguay; Fig. 1) highlights the significance of these Pampean lacustrine archives for reconstructing the past activity of the monsoonal system at a subcontinental scale.

Recent investigations in lake basins in Uruguay (~34°S, 54°W; Fig. 1) have shown a clear nutrient enrichment during the past 70 years associated with a well-documented increase in human impact in the region (García-Rodríguez et al., 2002; 2004; Inda et al., 2008). Present-day nutrient levels of anthropogenically-disturbed lakes indicate highly eutrophic conditions. Although, these conditions are also affected by other factors, such as basin morphometry, lake-use, catchment geology and climate, it seems clear that the most intense eutrophication is related to the human impact of the past century (Fig. 2). Paleolimnological results indicate that, over long timescales, similar trophic states to those observed at present existed during the Holocene, due to climate and sea level variations (García-Rodríguez et al., 2004; del Puerto et al., 2006).

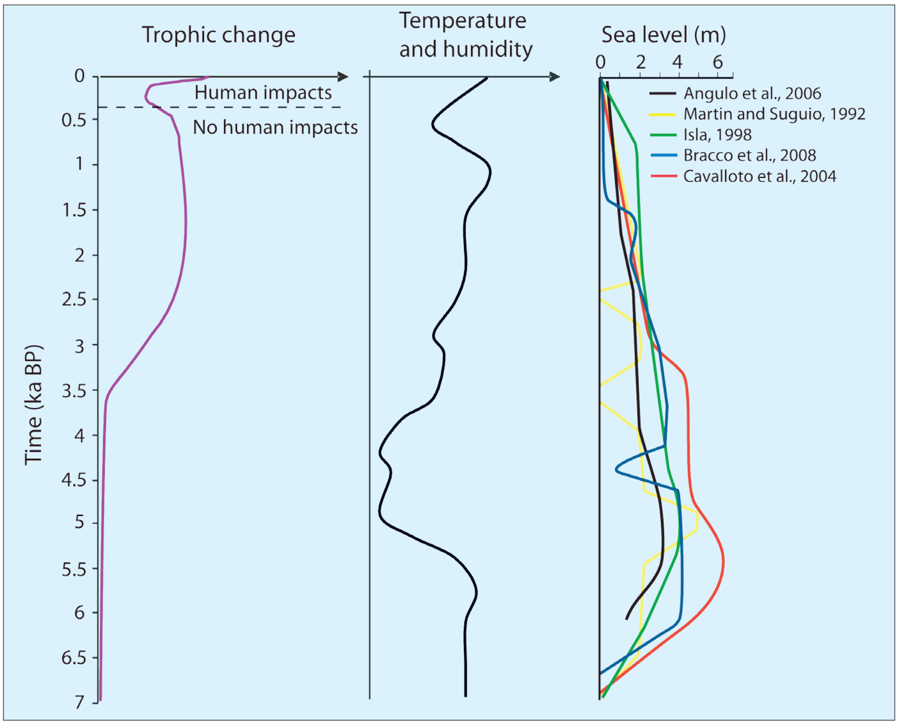

*Figure 2: Conceptual paleolimnological model displaying the relationship between trophic development of Uruguayan lakes (**purple line**), climate change in the region (**black line**) and Holocene sea-level curves (**colored lines**) observed in Uruguayan lakes. Temperature and humidity curves were reconstructed from opal phytolith data (Bracco et al., 2005; Inda et al., 2006; del Puerto et al., 2006; 2008; 2009). Sea level curves reconstructed from stratigraphical and topographical data.*

Holocene variability

The methods used on the most recent sediments of Laguna Mar Chiquita have now been applied down core on the older sediments. Results from these analyses show substantial regional hydrological variability since Late Glacial times and throughout the Holocene (Piovano et al., 2009). In addition, dominant dry conditions were observed during cold phases, such as those occurring during the mid-Holocene or the Little Ice Age (LIA), whereas wet conditions prevailed during warm climatic phases such as the Medieval Climatic Anomaly (MCA) or the late 20th century. Paleohydrological reconstructions suggest that the magnitude of the MCA wet phase was comparable to that of the present-day conditions. Thus, the results emerging from the PALEO-PAMPAS initiative have: a) lengthened the time-frame of existing instrumental datasets of climate variability; b) reconstructed past hydrological variability within a broad region of SESA including new sites in the Río de la Plata/Paraná Basin; c) resolved this variability at decadal timescale for the past 200-300 years and during older time windows; and d) analyzed past hydroclimatic scenarios at times of either little or no anthropogenic impact.

Similarly, research in Uruguayan lakes (Fig. 1) has focused on Holocene paleolimnological variations of coastal lacustrine systems linked to changes in sea level, as well as in climate and anthropogenic impact. Diatoms, chrysophyte cysts, opal phytoliths, and palynomorphs have been used as biological proxies for changes in lake trophic status, salinity, and climate. Diatom taxonomy studies of both recent and fossil taxa in Uruguay led to the description of 101 new diatom species and one new genus (Metzeltin et al., 2005; Metzeltin and García-Rodríguez, 2003). Although the new diatom species have not yet been calibrated versus environmental data, the ecological/trophic preferences have been documented. Trophic state and salinity changes were also inferred after adapting the cyst to diatom ratio findings (Smol, 1985) to temperate/subtropical lagoons influenced by sea-level changes (García-Rodríguez, 2006). The reliability of the ratio to infer changes in paleosalinities was successfully tested in other Uruguayan lakes by Inda (2009). In addition to biological indicators, geochemical proxies have been used to infer nutrients and lake productivity (Bracco et al., 2005; del Puerto et al., 2006; García-Rodríguez, 2006). These results demonstrated that the Holocene eutrophication of coastal lakes was controlled by sea-level variations and climate change. Higher trophic states were observed during marine regression events and climatic warming, while transgression and climate cooling led to lower trophic states (Fig. 2).

Thus, both modern limnological and paleolimnological data should be combined when designing the best possible management strategies, with paleolimnological data being especially useful for identifying the different causes and effects of eutrophication. Specific research efforts are currently being undertaken to compile an opal phytolith atlas as a taxonomic and ecological basis for both paleoclimatic and paleobotanical investigations. Concomitantly, opal phytolith assemblages from cattle enclosure sites are being studied to obtain quantitative data in view of distinguishing grazing and natural impacts on their distribution, thereby providing more realistic climate reconstructions. The combined use of opal phytoliths and pollen is thus an ideal approach to achieve more complete and reliable reconstructions of both climate and vegetation change. In the Buenos Aires province (Argentina), intensive fieldwork is being undertaken in several coastal lakes in view of multi-proxy reconstructions.

Conclusions and outlook

Although paleolimnological studies in the Argentinean and Uruguayan Pampas are relatively incipient, they have already provided critical information on the regional response of aquatic systems to climate variability. The combined results of these research initiatives highlight the key role of the subtropical region of South America (i.e., the transition between the tropics and the extra tropics) in deciphering the forcing factors of past changes in atmospheric circulation. Both Argentinean and Uruguayan Holocene paleolimnological records indicate similar paleoclimatic trends, i.e. dominant dry conditions were observed during cold phases, whereas wet conditions prevailed during warm climatic phases. To our knowledge, this is the first attempt to integrate paleoclimatic data for the whole Pampean region. In addition, our results underscore the need to reinforce paleoclimate research at mid-latitudes in South America, in an attempt to fully appreciate natural climate variability beyond the instrumental record, as well as to design new strategies for the sustainable development of ecosystems and natural resources.

Acknowledgements

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Results of recent sediment drilling activities in deep crater lakes

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Long terrestrial sediment records from deep crater lakes reveal precious paleoclimate archives.

Since the beginning of concerted efforts to extract long continental paleoclimate archives from lacustrine sediment records (see Leroy and Williams, 1996; Ariztegui, 1999), the terrestrial paleoclimate community has made substantial progress in providing precious paleoclimatic information from a number of sites in both hemispheres. Here we report on the latest achievements and progress made in three of these projects that concern large and deep crater lakes.

Laguna Potrok Aike

The Potrok Aike Maar Lake Sediment Archive Drilling Project (PASADO) is a deep lake drilling project sponsored by the International Continental Scientific Drilling Program (ICDP), as well as the German and Swiss National Science Foundations, Natural Sciences and Engineering Research Council of Canada, the Swedish Vetenskapsradet, and the University of Bremen (Haberzettl et al., 2007). Laguna Potrok Aike (51˚59.0' S, 70˚21.0' W; 113 m asl, diameter 3.5 km, water depth 100 m; Fig. 1a) is a late Quaternary volcanic crater lake in southern Patagonia (Argentina). From September through November 2008, sediment cores were retrieved by an international team from all funding countries and the United States using the GLAD800 drill rig. A total of 513 m of sediments were recovered from two sites in seven holes and resulted in a composite sediment length of 107 m, potentially representing a lacustrine archive of southern hemispheric environmental change of the past ca. 80 ka. Core sections and sediments are now stored and archived in the GEOPOLAR lake core repository at the University of Bremen. Various non-destructive analyses (multi-sensor core logger, digital photography and radiography, reflectance photospectrometry, magnetic susceptibility, XRF scanning) are almost complete while sub-sampling of the cores is underway for analyses of biotic and abiotic proxies (pollen, diatoms, chironomids, stable isotopes, rock- and paleomagnetics, geochemistry, grain size, mineralogy, pigments, organic petrology, microbial activity). Moreover, radiometric and luminescence dating techniques and tephrochronology will be applied to assure the best possible time control. The analysis of this unique Southern Hemisphere sediment record will provide insights into lacustrine ecosystem response to climate forcing since the onset of the last glacial, and will allow correlation of this record with marine and Antarctic counterparts to detect land-ocean-cryosphere-atmosphere interactions. Information on the latest progress of this research project can be found at http://www.pasado.uni-bremen.de or http://www.icdp-online.org/contenido/icdp/front_content.php?idcat=722, or by contacting Bernd Zolitschka.

Pingualuit Crater Lake

Pingualuit Crater Lake (61˚17'N, 73˚41'W; 520 m asl, diameter 3.4 km, cover photo) resulted from a meteoritic impact that occurred ca. 1.4 million years ago. Due to its unique bowl-shaped morphometry (270 m deep, almost perfectly circular), the lake bottom should have escaped glacial erosion. Based on a single punctual seismic survey, the uppermost 8.5 m of sediments were recovered (overall length of all sediment sections = 11.2 m) through the ice at a water depth of 260 m by an international team in early May 2007 (Fig. 1b). High-resolution physical (CAT-Scan, Multi Sensor Core Logger, diffuse spectral reflectance), geochemical (ITRAX core scanner, carbon and nitrogen contents, $\delta^{13}C$ of the organic matter), and magnetic (magnetic susceptibility, natural, anhysteretic, isothermal and saturation isothermal remanent magnetizations) analyses were performed. Two main lithofacies were clearly identified by the different measurements, which likely represent successive interglacial-glacial cycles. Most of the sediment consists of light grey silts containing several angular rock fragments, characterized by very low organic carbon content, relatively high density and magnetic susceptibility, and therefore suggesting deposition during

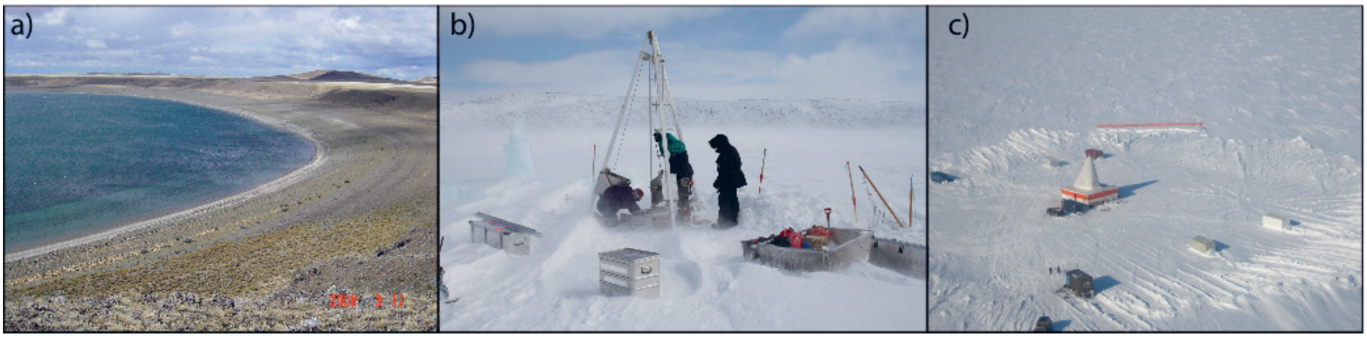

*Figure 1: **a**) Laguna Potrok Aike in southern Patagonia (Argentina) (photo: Reinhard Pienitz, Université Laval); **b**) Coring of Pingualuit Crater Lake sediments in early May 2007 (photo: Veli-Pekka Salonen, University of Helsinki); **c**) Aerial view of the drilling platform on Lake El´gygytgyn in April 2009 (photo: Kristina Brady, LacCore, Minneapolis).*

glacial conditions. Interbedded between this facies are at least two, decimeter-thick, organic-rich and finely laminated intervals likely representing ice-free periods. This is supported by the presence of fossil pollen, diatoms, chrysophytes, and chironomid head capsules, as well as high biogenic silica content (up to 20%) in sediments from these two intervals. In addition, preliminary Infrared Stimulated Luminescence (IRSL) dating indicates that the upper organic-rich layer has an age coeval with the last interglacial (Marine Isotope Stage 5, MIS 5), while the age of the lower organic-rich layer is consistent with an older interglacial, likely MIS 7. The sedimentary infill thus constitutes a unique long-term record of past environmental conditions for the Canadian and North American Arctic that will allow for comparisons with land-based, ocean and ice core records from the northern circumpolar region. Furthermore, the presence of a subglacial lake during the last two glacial periods can be inferred because the sediments escaped glacial erosion. Microstratigraphical analyses of thin sections are currently underway to define the depositional environments of each laminated interval. The Pingualuit Crater Lake drilling project is sponsored by the Canadian Foundation for Climate and Atmospheric Sciences. To be informed about the latest progress made within this research project, please refer to the websites (http://www.cen.ulaval.ca/pingualuit/index.html or http://www.cen.ulaval.ca/paleo/index.html) or contact Reinhard Pienitz.

El'gygytgyn Crater Lake

Lake El'gygytgyn is a 3.6 Ma old impact crater in northeastern Siberia (67°30'N, 172°05'E; 492 m asl). The lake has a roughly circular shape with a diameter of 12 km and a bowl-shaped bathymetry with a maximum water depth of 170 m. In May 2009, a six-month drilling operation in the El'gygytgyn Crater was completed by an international team from Russia, Germany, the United States, and Austria. Drilling was carried out from the ice, which had to be artificially strengthened to support the 75-ton drilling platform (Fig. 1c). This "Russian GLAD 800" was developed and operated by DOSECC and was permanently imported into Russia, where it will be available at no cost for the next five years for scientific drilling projects financed by the major funding agencies of the El'gygytgyn Drilling Project: ICDP, the US National Science Foundation, and the German Federal Ministry for Education and Research, with additional financial contributions by the Russian Academy of Sciences and the Austrian Federal Ministry of Science and Research. The project completed three holes in the center of Lake El'gygytgyn, reaching a maximum depth of 517 m below lake bottom. The upper 312 m of the crater fill consist of lake sediments. Extrapolating the sedimentation rates known for the last 300 kyr from cores recovered during site surveys, this lacustrine sequence likely represents the entire history since the impact event 3.6 Ma ago. This record opens new opportunities to investigate the natural environmental change from the Pliocene terrestrial Arctic, when global climate was significantly warmer than today, via the glacial-interglacial cycles since the Pliocene/Pleistocene transition 2.6 Mio years ago, to more short-term, millennial- to centennial-scale climate events. Comparison of the results with ocean and land-based records from lower latitudes will significantly enhance our understanding of the role of the Arctic in the global climate system. Underneath the lake sediments, a suevite layer of ca. 60 m thickness, containing impact glasses from melted target rocks, was penetrated, before more than 140 m of broken and fractured basement rocks were drilled, which had become shocked, brecciated, and uplifted during the impact event. Detailed investigations of the impact rocks will provide new information on the composition and nature of the meteorite that formed the crater and on the energy released during the impact. Of special interest are the acidic volcanic rocks, which form the target rocks of the El'gygytgyn impact. Their investigation will enhance our understanding of the impact and shock effects on such rocks, which has implications for comparative planetology. In addition to lake drilling, a 142 m drill core was retrieved from the permafrost deposits at the western shore of Lake El'gygytgyn. The core contains coarse-grained, ice-rich alluvial fan and near-shore lake deposits. Their investigation will provide information on the permafrost history and lake-level changes, both of which may have influenced the sedimentation in the lake center. After drilling, the permafrost borehole was permanently instrumented with a thermistor chain for future ground temperature monitoring as part of the Global Terrestrial Network for Permafrost (http://www.gtnp.org/index_e.html). For more detailed information on the drilling project see the websites http://www.elgygytgyn.uni-koeln.de, http://www.geo.umass.edu/lake_e, and http://www.icdp-online.org, or contact Martin Melles.

Conclusion

The long continental sediment cores recovered and the initial results obtained so far from these three crater lakes indicate that their paleoclimate records will provide new insights into the linkages between climate forcing processes and global paleoenvironmental changes, thereby improving the output of regional to global climate models. More lake drilling projects of this kind are presently underway or in the planning stage, which will make a significant contribution to a better understanding of past, present, and future climate dynamics.

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Paleolimnology and the restoration of aquatic systems

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Recent developments in environmental management include the rehabilitation, or even restoration, of aquatic ecosystems. This is enshrined in regional management strategies and international legislation, such as the European Water Framework Directive (WFD) that intends to return all waterbodies to "good ecological status" by 2015 (EU, 2000). At all scales, the management of these systems is dependent on the identification of a target condition for restoration. However, agreeing what the target condition should be is not easy. The different stresses caused by human activity need to be recognized and the target needs to accommodate the role of natural processes as well as the expected response from reduced human influence. Climate variability, in particular, has impacts on the hydrological balance of wetlands and lakes, some of which are sensitive to pressure, whereas others are resilient. The determination of natural ecological conditions frequently relies on instrumental data or short-term process studies. Given the range of natural variability and possible responses to human impacts, both approaches lack the timescale required to identify pre-impact (or reference) conditions, or to document the changes that have since taken place. In many aquatic systems, however, paleolimnological methods can provide the missing information.

Paleolimnology has sought to identify long-term changes in the condition of lakes and wetlands, and has correlated changing conditions to environmental and climate drivers at a range of temporal scales, often enabling the historic range of variability to be determined (e.g., Haberle et al., 2006). Paleolimnology can be employed to identify the initial point of change when the condition of a lake first departed from natural patterns of variability, and so can reveal the responsiveness of the waterbody to human impacts. Tracking environmental changes in sediment records can reveal pre-impact conditions, trajectories of change, and identify any signs of recovery. In this context, paleolimnological studies have made a major contribution to the implementation of legislation, such as the WFD (Bennion and Battarbee, 2007), especially with respect to the major problems of acidification and eutrophication.

Acidification of lake surface waters has been a matter of environmental concern for several decades. In the 1980s, paleolimnological methods helped establish that "acid rain" was the principal cause of acidification (e.g., Battarbee, 1990). Today, following major reductions in the emissions of sulphur and nitrogen gases, lakes and streams in acidified regions of Europe and North America are beginning to recover. The extent of the recovery so far, however, is limited, especially when judged by the difference between the current status of these ecosystems and the pre-acidification reference state revealed by paleolimnological analysis. Recovery is expected to continue but other influences on the ecology of recovering ecosystems, such as climate change, may cause entirely new ecosystem conditions to develop in the future. In this eventuality, the past reference conditions defined by using paleolimnology may become an impossible target for restoration but will nevertheless remain as a benchmark that will help assess future deviation from the natural background or reference condition.

Eutrophication is recognized as a major influence on the ecological condition of lakes and wetlands. While there have been considerable nutrient reductions in surface waters in the past few decades, the long history of human impact on the landscape makes it difficult to find minimally disturbed reference sites for many ecosystem types. In such cases, paleolimnology provides arguably the only technique for establishing a reference condition. Hence, to assist with implementation of the WFD in numerous European lakes, biological remains in sediment records combined with transfer functions have been employed to define ecological and chemical reference conditions, and assess deviation from the reference state (Bennion and Battarbee, 2007). Battarbee et al. (2007), in an analysis of paleodata from ~100 lakes, found few cases of eutrophication in Europe before ~1900, showing that conditions pre ~1850 represent a reference for efforts to restore surface waters to "good status" (see Fig. 1). Nevertheless, for some lakes with long histories of agriculture in their catchments, paleo-studies indicate that eutrophication can date back to the Bronze Age (e.g., Bradshaw et al., 2005), thereby suggesting that 1850 is an unsuitable baseline in such cases.

There are an increasing suite of instances where paleolimnological approaches have provided the critical temporal context to inform the challenging decisions that emerge for the management of "stressed" waterbodies worldwide. While restoring the past states identified by these techniques may be beyond the management capacity of our modified catchments, they plainly reveal the

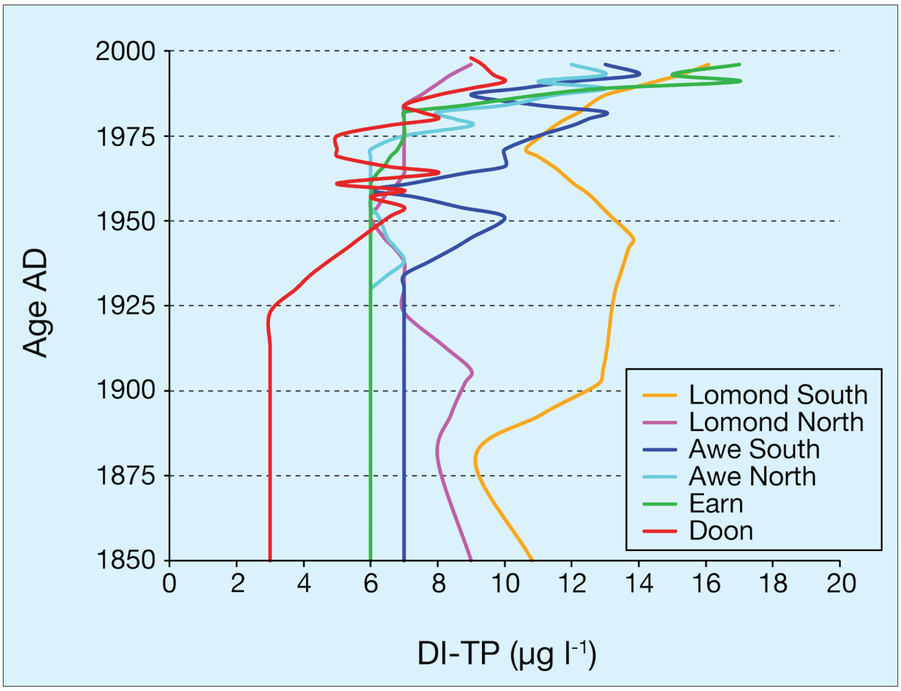

Figure 1: Diatom-inferred total phosphorus (DI-TP) concentrations (µg L^{-1}) for five Scottish loch basins, showing enrichment after 1850 AD (modified from Bennion et al., 2004)

dimensions of the impact industrialized society has had on the natural world, aid the identification of the timing and drivers of change, and establish a benchmark against which managers can evaluate the degree to which their restoration efforts are successful.

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For full references please consult:
www.pages-igbp.org/products/newsletters/ref2009_3.html

The 11th International Paleolimnology Symposium

Guadalajara, Mexico, 15 - 18 December 2009

We deeply regretted that the 11th International Paleolimnology Symposium, originally planned for June 2009, had to be postponed due to the influenza outbreak in Mexico.

The symposium will now be held in Guadalajara from the 15-18 December 2009. We would like to encourage the paleolimnology community to make a special effort to support the IPA symposium this year by coming to Mexico! On-site registration is available.

Sessions include:
- General paleolimnology
- Age-depth modeling
- Stable isotopes - advances in techniques and interpretation
- Organic geochemical paleoclimate proxies in lakes and bogs
- Lake-sediment archives of trace-metals and organic contaminants
- Paleolimnology of shallow lakes
- Varved and laminated lacustrine sediments
- Paleolimnological studies of arid regions of Eurasia
- Mountain lakes - exploring the sedimentary record of environmental change at higher altitudes
- Paleolimnology of high-latitude regions of the Northern Hemisphere
- Late Quaternary paleo-climate and -environmental records in lakes from the S. Hemisphere
- Human-environment interactions in the Americas
- Rapid events and human answers as reconstructed from lacustrine archives
- Quantifying the lake record of "paleo-precipitation" during the last 2 ka
- Floodplain lake sediments as archives for environmental history
- Paleolimnological applications in estuarine and coastal environments

We would also like to draw your attention to the "IPA Lifetime Achievement Award", which will be presented for the first time at this meeting, to Daniel Livingstone, Herbert Wright, Walter Dean and Frank Oldfield.

For more information see http://www.geofisica.unam.mx/paleolimnologia

The PAGES/CLIVAR Intersection: Vision for the future

Gavin Schmidt[1], Valérie Masson-Delmotte[2], and Intersection Panel Members
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The PAGES/CLIVAR Intersection Working Group is jointly sponsored by PAGES and the Climate Variability and Predictability (CLIVAR) project of the World Climate Research Programme (WCRP), and plays an important role in developing and implementing the overlapping research interests of both these programs. The formation of the Intersection was predicated on the idea that paleoclimate studies provide a useful adjunct to studies of modern climate variability and likely future change. Since its establishment in the mid-1990's, the goals of the Intersection have evolved with the changing focus of each parent organization. At the Panel meeting in Italy in June 2008, the goals were again updated and are now detailed in a new PAGES/CLIVAR Intersection Vision Document. In addition, the Panel decided that Valérie Masson-Delmotte will replace Eystein Jansen as Co-Chair, alongside Gavin Schmidt. The Panel also discussed the need for a representative from Asia, with particular expertise in analyzing the instrumental and rich documentary records of, for example, China, to join the Panel. Any interested candidates are asked to contact Gavin or Valérie directly.

A number of key scientific issues identified by the Intersection Panel will be addressed over the coming years. They are categorized into overarching cross-cutting issues, in addition to 4 more specific topical issues.

1) Overarching cross-cutting issues

- **Forward modeling of proxy data**, which means including the processes that produce proxy records directly within Earth System Models (ESMs) is considered of fundamental importance to further improving model-paleodata comparisons.
- **Reducing uncertainties in proxy reconstructions** (and data synthesis in general) are important for improving climate modeling targets and for understanding the intrinsic variability and forced response of the climate system.
- **Calibration of proxies against variability seen in the instrumental period** is a prerequisite for improved synthesis of proxy- and observation-based approaches, and requires interaction between paleoclimatologists and climatologists.

2) Climate variability over the last few millennia

Well-dated, high-resolution proxy reconstructions and model simulations incorporating estimates of natural and anthropogenic forcings for the last 2 ka offer opportunities to assess the natural decadal to centennial variability and forced responses in conditions similar to present. Despite progress in recent years, however, important uncertainties and caveats exist with regard to both empirical reconstructions and model estimates.

Upcoming activities will therefore focus on advancing process-based comparisons of models and data through an enhanced appreciation of forward modeling of specific proxies and at specific sites, including the role of downscaling from large-scale model simulations. The Paleoclimate Reconstruction Challenge (http://www.pages-igbp.org/science/prchallenge/) and the regional PAGES 2k Network (http://www.pages-igbp.org/science/last2millennia.html) will both play key roles in driving the science of this issue.

3) North Atlantic circulation changes

Interactions among the ocean, atmosphere, and sea ice are the likely cause of decadal to multi-decadal and centennial variability in the Atlantic meridional overturning circulation (MOC), with attendant impacts on spatial patterns of temperature and precipitation. Thus improved understanding of MOC variability may serve to improve the climate projections in these regions. Uncertainties in model parameterizations and the response of the climate system to anthropogenic forcings make projections of future MOC behavior unclear. Since multiple proxy records reflect MOC changes and their climatic impact, MOC variability is an excellent showcase for the value of using forward models of paleo-proxies, specifically ocean proxies, water, carbon and nitrogen isotopes, atmospheric chemistry, dust and sea salt aerosols.

The Intersection will support synthesis activities focused on data-model integration, particularly those that seek to improve mechanistic understanding of multidecadal variability and its impacts on, in particular, hydrology.

4) Hydrological changes and interactions with the land surface

Recent observations indicate that the tropical realm is expanding with increasing occurrence of drought in the sub-tropics. This trend is projected to continue under IPCC AR4 scenarios. There is also considerable evidence suggesting terrestrial climate variability is strongly influenced by hydrological and biospheric interactions and feedbacks. This is particularly relevant to high-latitude regions and the tropics, where it has been shown that feedbacks between the monsoon and land surface conditions have significantly influenced climate variability on all timescales.

ESMs that incorporate these feedbacks are now being used for future climate change prediction and need to be rigorously tested against the paleoclimate record. The emphasis of the Intersection will primarily be on initiating and supporting data synthesis activities concerned with data-model interaction. Particular emphasis lies on forward modeling of climate proxy data with relevance to low latitude changes in hydrology.

5) Tropical cyclones, extreme precipitation events

For some extreme events (e.g., tropical cyclones, droughts and floods), there is some theoretical basis for expecting changes in their occurrence and/or intensity, associated with changes in the background climate state. However, it is the nature of extreme events that they are rare, and so the observational record is often sparse. By targeting specific proxies (paleo-tempestology) or by increasing the appreciation of long documentary records available in Europe, US East Coast, Japan, China and Korea, an improved basis for the characterization of some extreme events could be developed.

For more detailed information on the planned activities of the Intersection, and the full Vision Document, please see http://www.clivar.org/organization/pages/pages.php or download the document from the PAGES Product Database at http://www.pages-igbp.org/products/ under "others".

Younger Dryas *Larix* in eastern Siberia: A migrant or survivor?

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Radiocarbon-dated larch cone and needles from Dyanushka Peat and pollen data from Lake Billyakh, located ~170 km south of the Arctic Circle, provide the first unequivocal evidence for larch trees growing locally prior to the Holocene and indicate reforestation of eastern Siberia by the early Holocene.

Knowledge of past forest change serves for a better understanding of the climate system, carbon cycle and genetic diversity, and can inform current predictions and conservation strategies (Prentice et al., 1992; Tarasov et al., 2007; Petit et al., 2008). Botanical records from high-latitude regions of Europe and North America indicate that boreal forests "became established during the Holocene interglacial (the past 11.6 ka) as a result of population invasion from southern glacial refugia and local expansion of small tree populations that survived the Last Glacial Maximum interval (LGM: ~25-17 ka) in cryptic refugia" (Petit et al., 2008). An extensive dataset of radiocarbon-dated macrofossils from northern Asia provides evidence that boreal trees advanced close to the current arctic coastline between 9 and 7 ka (MacDonald et al., 2000). Due to a lack of wood macrofossils older than 10 ka from the ~2000×2500 km^2 region of eastern Siberia between 108° and 145°E (Fig. 1a), there is no agreement on whether trees could persist there during the coldest phases of the last glacial period (Johnsen et al., 2001), including the Younger Dryas (YD: ~12.7-11.6 ka) and the LGM (Brubaker et al., 2005; Tarasov et al., 2007; Binney et al., 2009 and references therein).

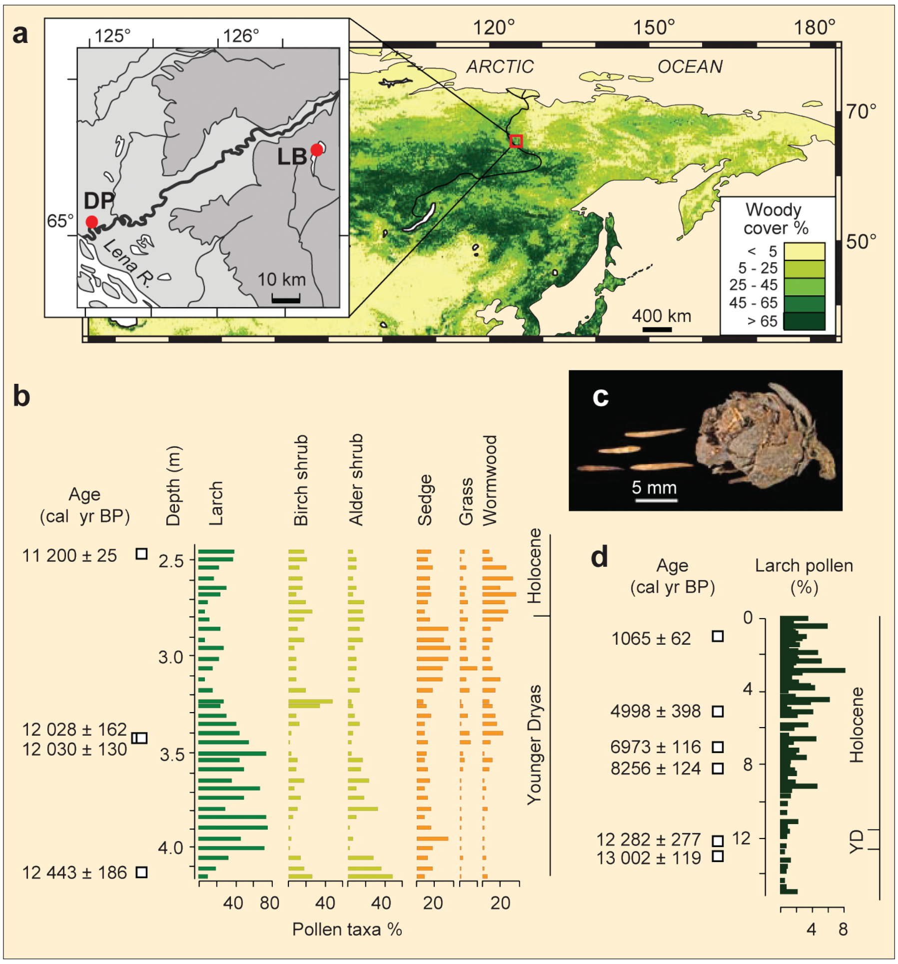

*Figure 1: **a**) Location of Dyanushka Peat (DP) and Lake Billyakh (LB) study sites (left) in the boreal forest belt of eastern Siberia (right, modified from Tarasov et al., 2007); **b**) Pollen diagram of the lowest part of the DP section, showing percentages of selected tree, shrub and herbaceous taxa and the calibrated radiocarbon ages (68% range); **c**) Photo of larch cone and needles from 340-345 cm depth in DP, dated to 12,030±130 (Poz-28087) and to 12,028 ± 162 cal yr BP (KIA26015), respectively (after Werner et al., 2009); and **d**) Chart showing the occurrence of larch pollen during ~15 ka in the short core from LB (after Müller et al., 2009). Radiocarbon years before present were converted to calendar years using the CalPal program (Danzeglocke et al., 2008).*

Results and discussion

Here we present unequivocal evidence from Dyanushka Peat (123 m asl), located in the western foreland of the Verkhoyansk Mountains, ~170 km south of the Arctic Circle (Fig. 1a), for larch trees (most probably *Larix cajanderi* Mayr) growing locally prior to the Holocene. Modern climate is extremely continental, with a mean temperature of around -40°C in January and about 15-19°C in July (Werner et al., 2009). Annual precipitation of 300-400 mm is relatively low but humidity is relatively high due to low evaporation. In addition, summer melting of the active permafrost layer provides a considerable amount of plant-available water. Cold deciduous forest dominated by larch, with shrubs growing in the understorey, occupies lower elevations, while tundra occurs above 700-1200 m asl. Dyanushka Peat reveals organic material accumulated in a former oxbow-lake exposed by the erosion of the Dyanushka River running from the Verkhoyansk Mountains to the Lena River (Werner et al., 2009). Analysis of pollen in the peat (Fig. 1b) demonstrates that larch trees and abundant birch and alder shrubs grew near the site between 12.5 and 11.2 ka, spanning the YD and early Holocene. The calibrated AMS radiocarbon dates on fossil wood (12,443 ± 186 cal a BP), cone (12,030 ± 130 cal a BP) and needles (12,028 ± 162 cal a BP) also identified within the peat (Fig. 1b-c) support the reconstruction of locally growing larch trees during the mid- and late YD. The herbaceous cover was mainly represented by sedges, with grasses and wormwood species becoming more abundant during the later phase of the YD after ~12 ka, likely indicating increasingly dry conditions (Fig. 1b). Recorded decrease in percentages of tree and shrub pollen corroborates such an interpretation. However, both pollen and macrofossil records indicate that this climatic change was not strong enough to destroy local larch stands.

Recently, Müller et al. (2009) published a radiocarbon-dated late glacial-Holocene pollen record from Lake Billyakh (340 m asl), situated in the western part of the Verkhoyansk Mountains, ~80 km from Dyanushka Peat (Fig. 1a). This publication demonstrated the continuous presence of larch pollen in the lake sediment during the past 15 ka (Fig. 1d). Larch pollen is known for its short-distance dispersal from the pollen-producing tree and generally poor preservation (Gunin et al., 1999; MacDonald, 2001 and references therein). This fact may explain its low percentages in the late glacial but also in many of the mid- and late Holocene pollen spectra from Lake Billyakh (Fig. 1d). The pollen data from Lake Billyakh, viewed together with the pollen and plant macrofossil records from Dyanushka Peat, strongly support our interpretation that local populations of larch persisted in the western foreland of the Verkhoyansk Mountains throughout the last 15 ka and survived the YD cold episode. The question, whether larch could survive the much longer, cold and dry LGM interval in situ or migrated into the study region as the result of the late glacial climate amelioration, needs more careful investigation.

The 9.36 m sediment core PG1755 recovered from the central part of Lake Billyakh provides for the first time in the study region a detailed pollen and vegetation record covering the past 50 ka (Müller et al., in prep.), as suggested by the age model (Fig. 2b) based on 6 bulk radiocarbon dates from the core PG1755 (Fig. 2a) and on 6 dates from the shorter core PG1756 (Fig. 1d). The correlation between the two cores was performed using pollen and magnetic susceptibility records.

A simplified pollen diagram (Fig. 2c) shows the predominance of herbaceous pollen during the last glacial, suggesting greater landscape openness compared with the Holocene. The quasi-continuous presence of larch, together with shrubby birch and alder pollen, throughout the whole record is the most striking feature of the core. The percentages of larch pollen reached high Holocene levels during the middle part of the last glacial (~40-30 ka), indicating growth of the larch trees around the lake at that time. The almost continuous record of larch pollen is difficult to explain by a long distance migration. The refugia hypothesis, which involves expansion of trees from local cryptic refugia, appears more plausible. The absence of larch in the pollen spectra from the early LGM (~25-22 ka) could indicate the disappearance of larch from the local vegetation. However, this is not likely to have been a large-scale disappearance, due to the re-appearance of larch pollen after ~22 ka without any significant changes in the pollen spectra, and thus in

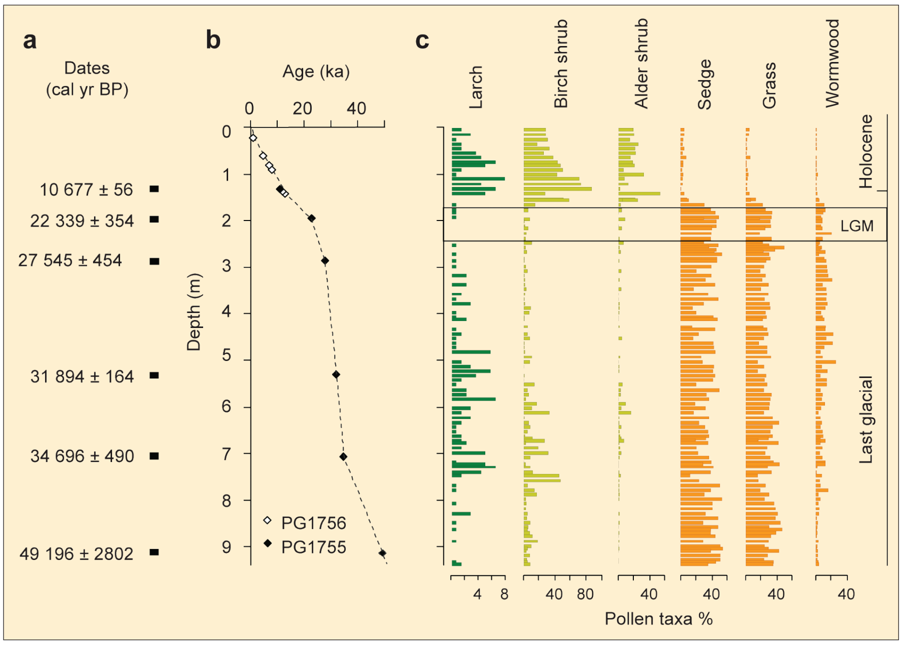

*Figure 2: **a**) The calibrated radiocarbon ages (68% range) from the long Lake Billyakh core used to construct **b**) The age-depth model; and **c**) Simplified pollen diagram showing percentages of selected tree, shrub and herbaceous taxa (Müller et al., in prep.).*

the glacial climate and environments. Further study, including counting of greater amounts of pollen, search for larch stomata and biomarker analysis, may help to resolve this problem.

Conclusion

Present-day extension of larch in the Arctic is limited mainly by the mean July isotherm of 10-12°C (MacDonald et al., 2000). It is plausible that the western foreland of the Verkhoyansk Mountains, the area where the Dyanushka Peat and Lake Billyakh are located, with its numerous lake and river valleys provided enough moisture and warm microhabitats to buffer larch trees against climatic extremes. The presence of larch populations during the late glacial and YD likely explains the quick reforestation of eastern Siberia by the early Holocene, and supports the molecular-based hypothesis suggesting the existence of high-latitude plant refugia during past glaciations (Abbott et al., 2000).

Data

All data from Lake Billyakh (PG1756 core) and from Dyanushka Peat used in Fig. 1 are available in the PANGAEA data information system (see http://doi.pangaea.de/10.1594/PANGAEA.708170 and http://doi.pangaea.de/10.1594/PANGAEA.716835).

Acknowledgements

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For full references please consult:
www.pages-igbp.org/products/newsletters/ref2009_3.html

Holocene Climate Change in the Asian Region

LIMPACS Workshop – Chandigarh, India, 5-8 March 2009

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The 3rd meeting under the "Salinity, Climate Change and Salinisation" working group of LIMPACS (Human impacts on lake ecosystems), a PAGES Focus 4 Working Group, was held in Chandigarh from 5-8 March 2009. This meeting followed those from October 2004 in Mildura, Australia and April 2007 in Nanjing, China. The meeting was jointly organized by Kumaun and Panjab Universities and was supported by PAGES, the Indian Council of Scientific and Industrial Research, and the Indian Oil and Natural Gas Commission. Over 70 participants attended from Australia, USA, UK, France, Germany, Russia, Bulgaria, Poland and China, as well as a strong contingent of Indian scientists and early career researchers.

This meeting focused on key extreme climate events (particularly decadal scale climatic changes) through the Holocene, across the Indian subcontinent and China including Tibet, with other contributions from studies in Mongolia, Lebanon, Siberia, Bulgaria, Botswana, California and Australia. Clear evidence was provided for the widespread impact of the Younger Dryas, 8.2 and 4.2 ka events, Medieval Warm Period and Little Ice Ages across the region, which, while evident, produce differential outcomes in terms of available moisture (Fig. 1). Another key theme addressed was the response of people to climatic fluctuations as expressed by societal collapse, migrations or changing technologies and economies.

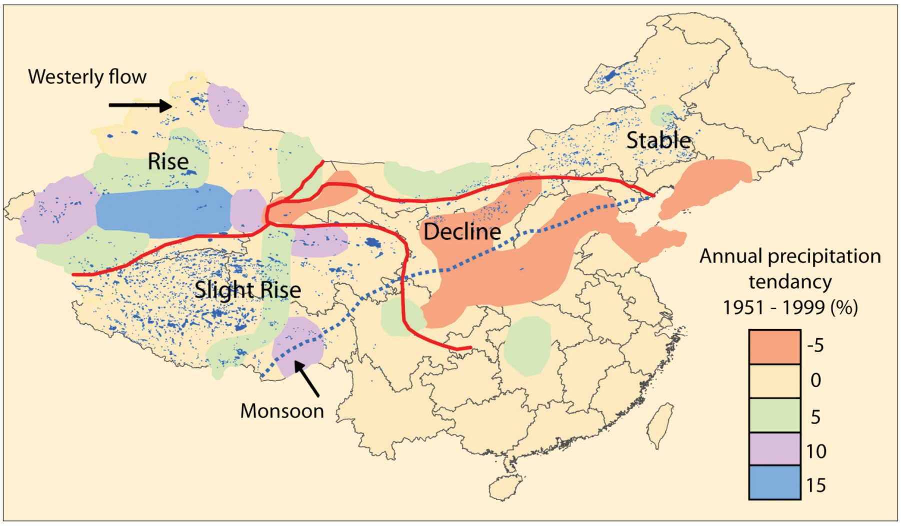

Figure 1: Water level changes across west China since the 1970s, based on topographic mapping and remotely sensed imagery. The levels of most lakes in western China fell through to the mid 1990s but have risen since due to increased rainfall.

Following the presentations, discussions were held that identified research priorities for the region. These comprised (1) stronger cooperation between climatologists and modelers, (2) improved dating techniques with better calibration, (3) an intention to generate better estimations of actual climatic parameters (temperature and humidity) through proxies and (4) a plan to develop a regional database of records of climate and water budgets for Asia, especially across the Indian subcontinent. It was also felt that a better understanding of the connection between climate change processes and civilization and culture would aid the prediction of climate-driven catastrophes and mitigate their impact in the future.

The proposal to develop a regional network, first tabled at the Nanjing meeting, was developed with a proposal to launch the "Across the Third Pole" (ATP) research network, to encourage the development of regional syntheses to explore the impact of recent climate change and human impact on lake ecosystems across the Himalayan slopes and Tibetan Plateau. It was agreed to meet again in Bulgaria in September/October 2011 to collate recent records of human impact, and to advance the aims of the ATP network by identifying sites and supporting research in key sites across the region.

East African Quaternary: Lessons from the past for the future

The 2nd Eastern African Quaternary Research Association (EAQUA) Workshop – Addis Ababa, Ethiopia, 21-24 May 2009

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The 2nd East African Quaternary Research Association (EAQUA) workshop was held in Addis Ababa, Ethiopia from 21-22 May 2009, followed by a post-workshop field trip to the Main Ethiopian Rift on 23-24 May. The workshop was organized by the Department of Earth Sciences, Addis Ababa University in collaboration with EAQUA; and was sponsored by PAGES, START, INQUA, the Paleo-Anthropology Scientific Trust, British Institute in Eastern Africa, the Revealing Hominid Origins Initiative, and local institutions (Addis Ababa University, Authority for Research and Conservation of Cultural Heritages, and Ministry of Science and Technology). The Workshop was officially opened by the State Minister of the Ministry of Culture and Tourism of Ethiopia.

The primary objectives of the workshop were to strengthen and enhance active communication on Quaternary research issues in the Eastern African region, and to serve as a forum for initiating new

Figure 1: Participants of the EAQUA Workshop

and strengthening existing collaborations and networking among the East African Quaternary community. Another objective was to bring together paleoscientists who work in the region under the PAGES science structure, in particular Focus 2 (Regional Climate Dynamics) and Focus 4 (Human-Climate-Ecosystem Interactions). The workshop also aimed to assess the opportunities and challenges in research, training and capacity building.

More than 50 researchers participated from the Eastern African region (Ethiopia, Kenya, Tanzania, Uganda) and other parts of Africa (South Africa and Nigeria), as well as from Belgium, France, Germany, Ireland, Switzerland, UK, and USA. Thirty oral papers and 8 posters were presented, organized in five major themes spread over two days.

During the first and second sessions, the climate of the last 2000 years, long-term monsoon variability and abrupt changes in East Africa were described using proxy rainfall data from many archives (lake and cave sediments, speleothems, tree rings, and pollen). Presentations in these sessions established the local and regional climate variations and emphasized the need for an integrated approach to understand the variations with respect to global climate forcings. Papers in the third session addressed the paleo-vegetation history of parts of Ethiopia, Kenya and Nigeria, using pollen, buried charcoal and soil organic matter, and related climate variations to societal development histories.

Archeological and fossil records in East Africa were presented in the fourth session. New, as well as published data from hominid, archeological and historical sites in Ethiopia, Kenya, and South Africa were presented. In the last scientific session, presentations addressed the impact of global and climate changes in East Africa, as well as assessment of adaptations and vulnerability. Studies from Kenya, Tanzania and Uganda showed the impacts of climate changes on biodiversity and hinted at adaptation mechanisms and mitigation measures.

The scientific presentations were followed by a discussion on potential workshop products, and plenary talks by representatives of INQUA, PAGES, and PAST, who presented brief program backgrounds. The final session of the workshop was dedicated to general discussion, EAQUA matters, and the way forward. The general discussion emphasized the need to strengthen EAQUA both in terms of membership and its institutional activities. To this effect, it was agreed that:

- Proceedings of the workshop should be published in four synthesis papers addressing the four major themes.
- Networking among EAQUA members and Quaternary researchers in East Africa should be strengthened.
- EAQUA should increase its visibility through webpages and other avenues.
- The draft EAQUA Constitution should be circulated among members for comments and be rectified during the next meeting.
- The next EAQUA workshop should be held in Zanzibar in 2011.

During the post-workshop field trip, participants visited archeological (Melka Kunture, and Tiya-World Heritage Site), geological (crater lakes, rift-plateau escarpment, the Main Ethiopian Rift, the Lakes region: lakes Awasa, Shala, Abijata, Langano and Ziway), and biodiversity sites (Munesa forest). The geological, environmental and vegetation histories of the sites were explained by experts in the group, followed by lively discussions.

The workshop participants also enjoyed a visit to the Ethiopian National Museum in Addis Ababa, where world-famous hominid fossils are on display.

Data-assimilation techniques for paleoclimate data

Vienna, Austria, 25 April 2009

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Paleoclimate modeling provides a means for formulating and testing hypotheses, for example, quantifying the response of the Earth System to different forcings. Moreover, Earth System models provide a comprehensive framework for exploring couplings and feedbacks between the various components of the system. This type of analysis is of special relevance for detecting thresholds in the Earth System. The joint utilization of paleoclimate reconstructions and paleoclimate modeling require methods for an objective comparison of proxy data and modeling results.

Data assimilation has become an important approach in this regard. It allows for estimation or forecast of the state of the atmosphere and oceans. However, this method is not readily available for paleodata due to their sparse spatial distribution and the uncertainties associated with proxy reconstructions. This led a group of 12 scientists from Europe, Japan and the United States to convene at a workshop to debate the applicability of the various techniques in a paleoclimate context.

Several data-assimilation techniques exist, including variational techniques, sequential filtering and statistical methods (e.g., Monte Carlo methods). All these techniques aim to reduce the model-data misfit that is summarized in a so-called "cost" function (a measure of the deviation between modeled state and data). One technique requires an adjoint (which provides the sensitivity of the actual state with respect to each control variable), while other techniques require a large ensemble of states. Problems common to all methods are model uncertainties, data uncertainties, and defining the cost function. Models have systematic errors, which if not properly considered, can lead to biases in state estimations, for example, in the representation of turbulent mixing. Data uncertainties are equally important. Such uncertainties arise because of errors in the measurement and calibration, and in the age model. Dealing with semi-quantitative data, such as proxies for flow speed, appears also possible in this framework.

Several groups have recently started to work on the assimilation of paleo-data into numerical models of the circulation in the ocean and/or atmosphere (e.g., Hargreaves et al., 2007). The majority of work has been directed towards the state of the large-scale ocean circulation during the Last Glacial Maximum (LGM, ca. 21 ka) since the corresponding proxy-data coverage is relatively good, especially for the oceans (Lynch-Stieglitz et al., 2007; MARGO Project Members, 2009; see http://www.glacialoceanatlas.org for further details). The goal is to find the best estimate of the LGM ocean circulation that is dynamically consistent with model and proxy data (Marchal and Curry, 2008). These methods have incorporated tracer observations from sediments, such as stable carbon-isotope measurements over the whole depth range of the oceans to estimate the glacial circulation. The underlying data synthesis is already in progress. A grand challenge for these efforts is a LGM "reanalysis" project, which is aimed at estimating the climate state at LGM, as well as the changes from LGM to present.

New efforts are also underway in order to assimilate proxies to reconstruct surface temperature of the last 600 years (Goosse et al., 2006). This approach is complementary to the ongoing efforts to estimate the temperature evolution during the last millennium and will allow for a synoptic view. In addition, the underlying ensemble method allows the influence of uncertainties in the model physics and in the forcing to be reduced. With the aim of understanding ocean circulation in a high-CO_2 world, one project will assimilate a global set of paleoceanographic reconstructions for the Mid-Pliocene into an ocean general circulation model.

The benefits of applying data assimilation techniques to paleo-data are large. These methods can provide dynamically consistent, quantitative reconstructions of past climatic states with information on the uncertainty of the state. Paleo-data assimilation can test the consistency of these data with models and the consistency between different types of proxies. It could also provide guidance about locations where new observations would result in much improved estimates of climate states (Fig. 1). In summary, paleo-data assimilation will allow for quantitative evaluation of climate states and for hypothesis testing well beyond the relatively short span of instrumental records.

The workshop served as a first step towards implementing PAGES Cross-Cutting Theme 3 "Modeling". By bringing together scientists at early stages of their intended research, the workshop helped to create a network between the involved groups at an international level. Two paleodata assimilation sessions are now being planned for the European Geosciences Union General Assembly in May 2010.

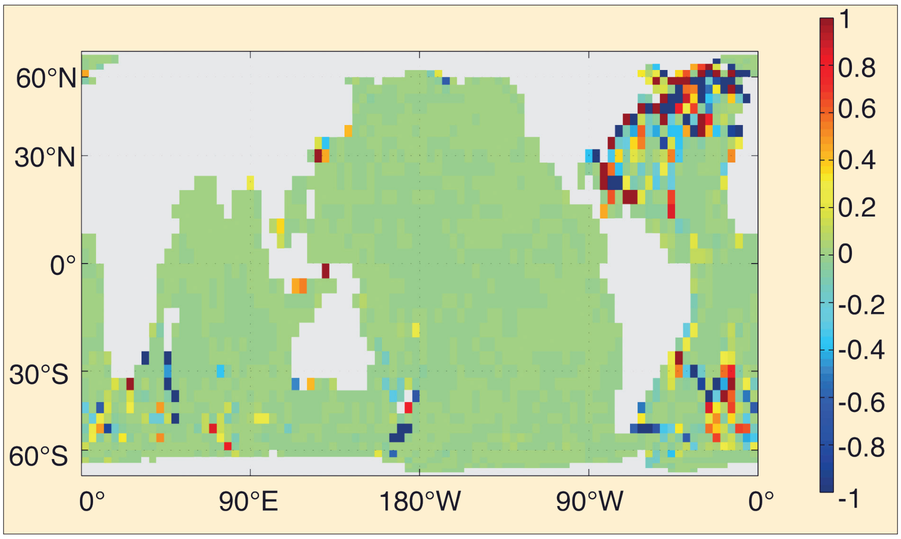

Figure 1: Combining paleo-data with adjoint models can provide critical information on important gaps and help in selecting future coring locations. Here, for example, the sensitivity of the strength of the North Atlantic meridional overturning circulation with respect to bottom topography (in units of 10^{-4} Sverdrups per meter) was computed by an adjoint of an ocean general circulation model (Losch and Heimbach, 2007). This shows that reducing the height of the topography south of New Zealand increases the transport through the Drake Passage and increases the strength of the North Atlantic overturning circulation, with red grid squares indicating the best locations for obtaining highly sensitive core archives (Figure modified from Losch and Heimbach, 2007).

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Peatland archives of Holocene climate variability

Vihula Manor, Estonia, 17-20 May 2009

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Paleoclimatology got its start with 19th- and early 20th-century studies of peatland stratigraphy in northern Europe by Steenstrup, Blytt, Sernander, von Post, and others. Peatlands, particularly ombrotrophic (usually *Sphagnum*-dominated) systems, continue to be an important archive for Holocene paleoclimatology, paleohydrology and biogeochemistry, due to their high sensitivity to climate variability and sub-decadal to sub-centennial temporal resolution over timespans ranging from the past few centuries to the entire Holocene. Recent advances in dating and methodology, together with new studies in Europe, Asia, the Americas and New Zealand, offer opportunities for international scientific coordination and synthesis of existing records, priority-setting for future studies, and integration with Earth System models and other paleo-archives.

To these ends, PAGES sponsored a workshop on "Peatland Archives of Holocene Climate Variability and Carbon Dynamics" at Vihula Manor in rural Estonia from 17-20 May 2009. The workshop, co-sponsored by INQUA, the US National Science Foundation, the Quaternary Research Association, and the University of Tartu, was organized by Stephen T. Jackson (University of Wyoming), Edgar Karofeld (University of Tartu), Robert K. Booth (Lehigh University), Dan Charman (University of Plymouth), and Bas van Geel (University of Amsterdam). The workshop was attended by 34 scientists from 15 countries in Europe, North and Central America, and Asia, and included 2½ days of discussions and a ½-day field trip to a local peatland.

Plenary presentations centered on refinement and development of paleoclimate proxies (R.K. Booth, J. Nichols), challenges imposed by scale, sensitivity, and uncertainty estimation (D. Charman), high-resolution dating and ^{14}C wiggle-matching (B. van Geel, M. Blaauw), peatland carbon dynamics (D. Beilman), and comparison of peatland records with other archives (A. Korhola, B. van Geel) and with paleoclimate models (S. Harrison). Initial breakout sessions concentrated on carbon dynamics, proxy and chronology refinement, and forward modeling of peatland response to climate change, with a second breakout series focused on development of peatland-archive data networks, and integrating peatland records with other archives and with Earth System models.

Key findings and recommendations include:

- Peatland archives can provide sensitive records of hydrology and carbon dynamics with decadal to centennial precision across large reaches of the globe.
- Standard proxies (testate-amoebae, humification, macrofossils) are being complemented by emerging proxies (organic biomarkers, stable isotopes), each with strengths and weaknesses. Integration of multiple proxies will strengthen inferences and differentiate climate variables.
- Application of all proxies will benefit from taphonomic and process-based studies and from increased replication.
- Paleoclimatology will benefit from a network of high-resolution peatland records focusing on specific time-intervals (e.g., last millennium, mid-Holocene, last deglaciation).
- Quantitative assessment of errors and uncertainties in proxies, age-models and inferences deserves increased attention.
- Development of process-based models of peatland-system responses to climate change at timescales of years to centuries will provide a means for connecting with climate-model predictions in a forward-modeling context, and clarify mechanisms that drive peatland proxy variables.
- Peatland archives comprise a store of information on past carbon dynamics and peatland responses and feedbacks to climate change. Synthesis of existing records can address questions concerning the role of peatlands in the global carbon cycle as sinks and sources.
- Systematic integration of peatland records with those from other archives will be fruitful in differentiating climate variables and drivers, and in detecting changes at different temporal scales. An important but surmountable challenge is posed by chronological correlation among records.
- Archival and research databases of peatland records are needed to support data synthesis and application.
- International collaboration and coordination should target collection of new data from key regions and time periods. Research priorities should be in general accord with broader goals of the international Earth System history and paleoclimate communities.

Follow-up activities, including database development and synthesis, preparation of review papers, and additional workshops and working groups are underway to address these recommendations.

Note

For more information on the workshop, please see: http://www.lehigh.edu/~rkb205/peatworkshop/

*Figure 1: **a**) Photo of meeting participants (S. Jackson); **b**) Photo of Männikjärve Bog in central Estonia (E. Karofeld).*

Climate variability, forcings, feedbacks and responses: The long-term perspective

NCCR CLIMATE
Swiss Climate Research

8th International NCCR Climate Summer School – with participation of IGBP PAGES
Grindelwald, Switzerland, 30 August – 4 September 2009

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The 8th International NCCR Climate Summer School was held in collaboration with PAGES and brought together 74 PhD and post-doctoral students from 16 different countries, mainly from Europe but also Japan, Australia, Chile, Russia, Canada and the USA, as well as18 keynote speakers and workshop leaders. The meeting was held in Grindelwald, a small alpine village located in the Jungfrau region of the Swiss Alps. Participants gathered together to learn about various aspects of paleoclimate science, including proxy reconstructions and modeling, to understand the nature of feedbacks, forcings and their impact on the climate system. The agenda of the meeting, included keynote lectures that were followed by lively discussions, poster sessions, workshops, excursions and group presentations by the participants.

The keynote lectures were structured around four topics that focused on: (1) long-term perspective of climate variability; (2) use of climate models, data assimilation, and reconstruction techniques to simulate present, past and future climates; (3) the climate system responses to forcings and feedbacks, and (4) the impacts of climate change on the hydrological cycle, on ecological responses to changes in soil moisture, and on the economy, specifically on global food security. Most of the lectures were focused on areas of research that remain open to discussion and on future directions to follow. Among the recurring topics were the forcing mechanisms responsible for the Medieval Climate Anomaly-Little Ice Age climate shift, future sea level rise, the role of clouds, aerosols and soil-vegetation feedbacks on climate variability and sensitivity, and the existence of tipping points in the climate system (Fig. 1).

Poster sessions took place every day during coffee breaks, thus allowing for informal discussions between participants as well as with lecturers. These sessions started with short individual oral presentations, providing an overview of the research presented in each poster, to help identify potential interlocutors. Each participant had prepared a poster about his/her specific topic and used the time allotted to get useful feedback and to discover or question details of others' work. The broad range of time and spatial scales covered by all posters and the variety of issues addressed, processes analyzed and methods presented made it easy for everyone to always find constructive discussion partners.

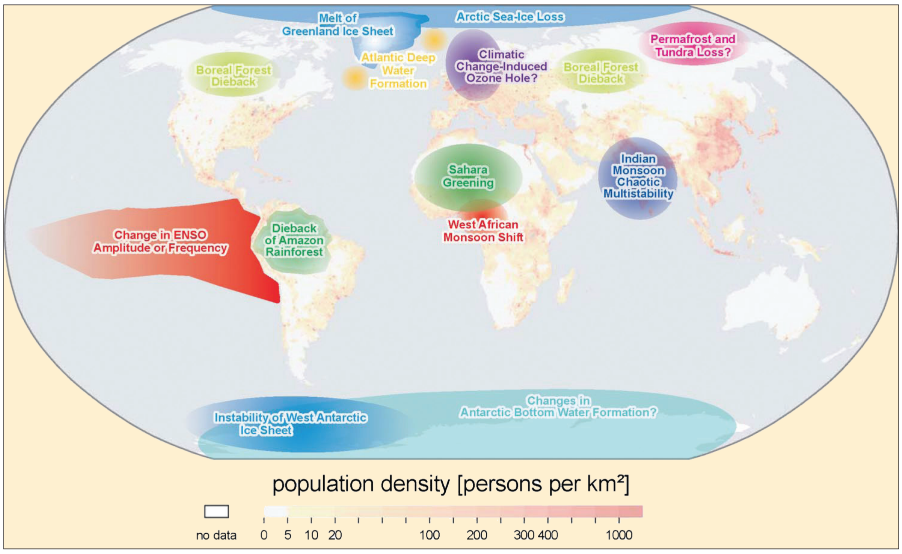

Figure 1: Map of potential policy-relevant tipping elements in the climate system, overlain on global population density. Subsystems indicated may pass a critical threshold this century at which a tiny perturbation can alter the state or development of the system (from Lenton et al., 2008).

In addition to the interesting lectures and engaging poster sessions, students were given the opportunity to participate in two out of four hands-on workshops: (1) relevance of tree-ring detrending for long-term climate reconstructions; (2) Kalman filtering and data assimilation; (3) climate reconstructions using annual and non-annual sedimentary archives; (4) assessing risks of natural catastrophes in a changing climate.

Another exciting activity was the students' participation in one of three different fieldtrips: (1) to discover the geology and glaciology of the area; (2) to practice dendrochroological sampling techniques in a forest gradient; (3) to explore some valley features through a guided iPhone excursion. These excursions allowed the students to get a better understanding of the spectacular landscape, history and ecology of the Swiss Alps.

The summer school ended with group presentations prepared by the participants over the week. Five topics covering various aspects of the science of climate were presented: Extreme events, model uncertainties, the anthropocene, internal variability vs. external forcings, and climate reconstructions. The diverse topics favored the grouping of participants with similar research interests, thereby allowing more specific discussions. By incorporating examples from the keynote lectures, these presentations also served as a review of the most important issues raised during the week

Thanks to the review of current climate research as well as its interdisciplinary nature, the 8th International NCCR Climate Summer School was a great success for its organizers and participants. The faculty, keynote lectures and workshop topics were very well selected, and the location in particular made it a unique experience.

Acknowledgements

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Mechanisms of Quaternary climate change: Stability of warm phases in the past and in the future

European Science Foundation – Austrian Science Fund Conference with the University of Innsbruck – Obergurgl, Austria, 6-11 June 2009

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The most important sources of information on past climate change are derived from paleoclimatic records such as marine sediments, terrestrial archives and polar ice cores, as well as from climate models. These archives are highly complementary, giving a wealth of precious quantitative information on the nature and causes of climate variability and change.

To critically look at climate variability during past interglacials (IGs), approx. 100 scientists from five continents gathered at the Obergurgl University Centre, Austria for this ESF-FWF Conference in partnership with the University of Innsbruck.

The Conference was structured along six sessions on different emerging topics in the field of past IGs. The first session addressed the comparison of different IGs over the last million years, with some specific talks on how IGs are recorded in different climatic archives such as ice cores, marine sediments and terrestrial archives. The role of orbital parameters and feedback mechanisms emerged as key factors in the regulation of past climate during IGs, however, a consistent self-sustained model-based hypothesis is still lacking.

The second session covered the variability and stability of warm phases. Short-term variability, reconstructed thanks to the high-resolution analyses of ice cores and other archives, has shown that IGs are not as stable as initially thought, and that regional variations in the climatic archives have to be clearly addressed in order to better understand the variability of the climate systems during these periods.

Problems arising from modeling the climate of warm phases were addressed in the third session, in an attempt to improve the prediction of future scenarios. In particular, the dynamics of vegetation and the carbon cycle during the present and past IGs were discussed. It emerged that investigations on this topic must be based on high quality atmospheric CO_2 and carbon isotope data, as well as on marine archives for carbonate production and paleoproductivity. Accordingly, one of the highlights of the conference that fuelled intense discussions was the presentation of the first high-precision Holocene isotopic greenhouse gas record (e.g., Fig. 1; Elsig et al., 2009).

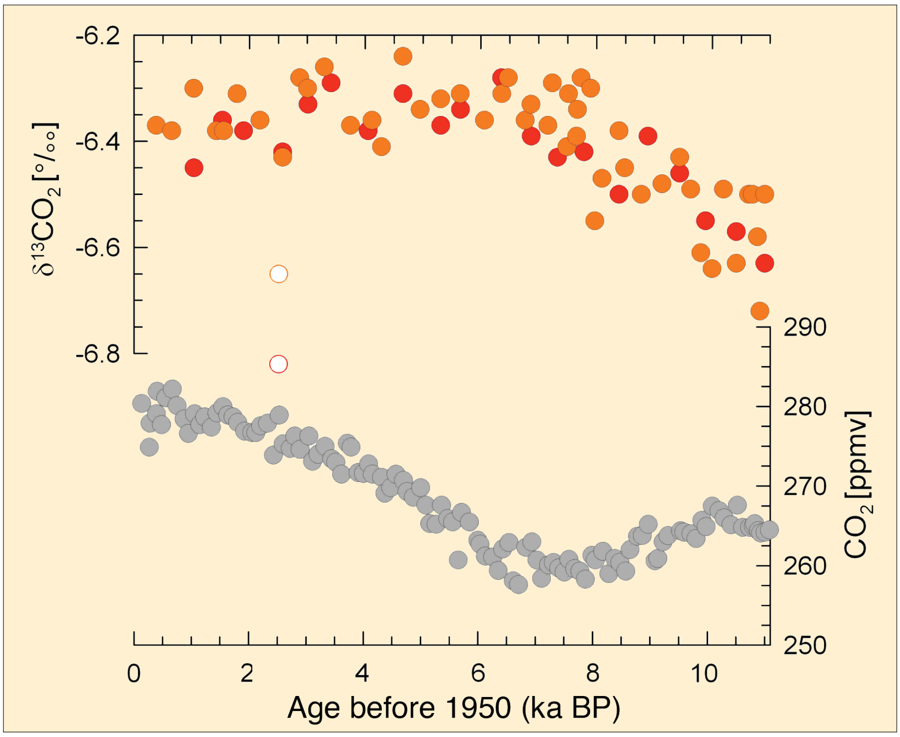

*Figure 1: $\delta^{13}CO_2$ (**red** (sublimation method), **orange** (Cracker method), and **white** (outliers) circles; Elsig et al., 2009) and CO_2 concentrations (**gray** circles; Monnin et al., 2001; Flückiger et al., 2002) measured in air trapped in ice from Dome C, Antarctica, during the Holocene (Figure modified from Elsig et al., 2009).*

The response of ice sheets to interglacial warming and their impact on sea level was the subject of the fourth session of the conference. Past changes in sea level were heavily influenced by the waxing and waning of the large Northern Hemisphere continental ice sheets, and thus cannot provide a direct analog for the sea-level rise in the future. However, it emerged from discussions that it is difficult to project sea level rise in response to ongoing global warming if the past response of the Greenland and Antarctic ice sheets to warming cannot be better quantified. The close combination of paleoclimatic data analyses and modeling efforts will strongly help to put the evolution of present sea level rise in the right perspective.

A modeling session then paved the way for discussion on how and when the present interglacial, the Holocene, would end. Several hypotheses, based on orbital and anthropogenic forcing were addressed, pointing out that further high spatial and temporal resolution models are needed to better understand the processes that will drive the inception of a new ice era.

Finally, the role of socio-economic aspects and impacts of climate change were addressed through specific talks in a dedicated session and open discussions. This session stressed the need for close collaboration between scientists involved in paleodata production and analyses, and scientists working in the field of climate change impact at the socio-economic level.

A “Forward Look” Plenary Discussion was organized with the aim to develop a vision on how climate sciences should evolve in the coming years. Many themes for future research in the field of paleoclimate emerged from the discussion, in particular key issues relating to sea level change and modeling during IGs, and the duration of the present IG. The latter point appears crucial considering that current CO_2 concentrations have taken us out of the Quaternary range, putting us in a new era, the Anthropocene.

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Towards a global synthesis of the climate of the last two millennia

Workshop of the PAGES 2k Regional Network – Corvallis, USA, 7 July 2009

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Research on the last 1-2 ka has resulted in several multi-proxy reconstructions of global and hemispheric temperature, and other climatic parameters (e.g., Rutherford et al., 2005; Mann et al., 2006; 2008; Luterbacher et al., 2004). Despite this, we still do not sufficiently understand the precise sequence of changes related to regional climate forcings, internal variability, system feedbacks, and the responses of surface climate, land-cover, biosphere and hydrosphere. Furthermore, many parts of the globe lack adequate paleorecords for comparison with model simulations, and high-resolution instrumental datasets are sparse.

To address these knowledge gaps, PAGES developed the Regional 2k Network—a set of Working Groups (WGs) that collect and process the best available time series and spatial reconstructions of important climate system variables for a given region (including the adjacent ocean; Fig. 1). Several WGs built on existing projects and are, therefore, at a mature stage in their research, while other WGs have only recently formed. All the WGs recently came together for a one-day workshop in Corvallis, USA to discuss regional results, exchange information on approaches and techniques, and develop a coordinated strategy for outcomes and syntheses.

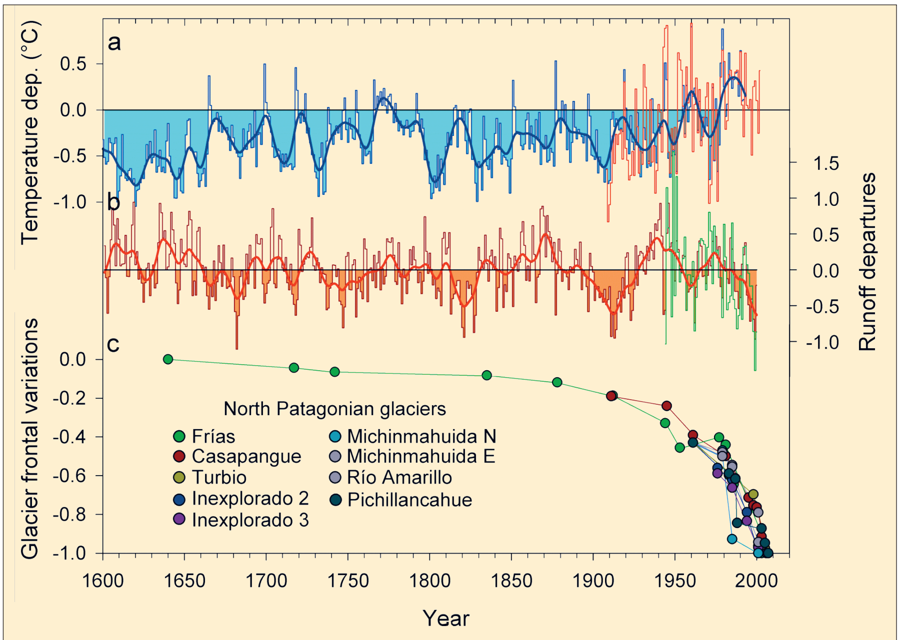

Figure 1: Recent results from the LOTRED-South America 2k effort. Climate variations in the Northern Patagonian Andes during the past four centuries. ***a****) Summer (Nov - Mar) temperature changes (expressed as departure from calibration period 1908-2003) inferred from a regional network of* Fitzroya cupressoides *tree-ring chronologies in northern Patagonia (blue line; Villalba et al., 2006) plotted with the instrumental summer temperature variations for northern Patagonia (red line; Jones and Moberg, 2003) for the interval 1908-2003. The correlation coefficient observed v's reconstructed is r = 0.75 (n = 85, p< 0.01).* ***b****) Tree-ring based reconstruction of Dec-May stream flow deviations (expressed as departure from calibration period 1943-1999) of Río Puelo from 1599 to 1999 developed from a combination of* Austrocedrus chilensis *and* Pilgerodendron uviferum *chronologies (red line; Lara et al., 2008). It correlates significantly with the instrumental Rio Puelo stream flow recorded at Carrera Basilio, Chile (green line) for the period 1943-1999, at 99% confidence level (r = 0.65). Thick lines in both a and b represent 15-year cubic splines to emphasize low frequency variations in the reconstructions.* ***c****) Frontal variations of selected glaciers in the North Patagonian Andes. Total retreat of the glacier with the longest record (Glaciar Frías; AD 1660-2007) was normalized to -1.0 and the frontal variations of the other glaciers were adjusted to this range of variation. Glacier frontal variations are from Villalba et al., (1990), Bown and Rivera (2007), and Masiokas et al. (2008; 2009). The thin interpolation-lines in (c) are drawn to enhance the readability and do not suggest linear trends between two data points.*

Following an introductory talk by Heinz Wanner, the state-of-the-science for each group was presented. Representing Europe and the Mediterranean, Jürg Luterbacher presented a compilation of annual- and lower-resolution proxy records, and highlighted efforts towards spatial reconstructions and associated uncertainty estimates for a dynamical understanding of European climate. The focus of this WG now is to push the temporal scale of spatial reconstructions to cover 2 ka, combining all available proxies, data-model comparison and data assimilation exercises.

The North American WG is also well placed to move towards synthesis. Caspar Ammann highlighted the extensive network of proxy records available and outlined new methodological advances that will provide greater understanding of the physical mechanisms behind past climatic changes. Future goals of this WG are to produce a review of the available data and to cross validate with model output.

A concerted South American effort has resulted in a recently published series of regional syntheses of data sets from a variety of paleoclimate archives (see details on website). Ricardo Villalba presented an overview of these results, and showed that the spatial and temporal coverage of the data is adequate to develop multi-proxy field reconstructions for southern South America for the past ca. 500 years. Efforts are now being directed towards homogenizing instrumental data sets for calibration of proxy data series, and increasing their temporal and spatial coverage.

The Asia 2k WG is under development. Edward Cook presented multi-proxy reconstructions of the Asian monsoon, temperature and drought from Eastern Asia, the Altay Mountains and Indochina, respectively. The next step for this group is to consolidate the team, followed by a review of the available data and gaps in knowledge.

The African 2k WG is also still developing. Mohammed Umer and David Nash presented an overview of available data for Eastern and Southern Africa, respectively, particularly highlighting the importance of understanding variations in rainfall and occurrence of extreme events (e.g., droughts). Once group participants are finalized, this WG will undertake a review and integration of high-resolution time series.

The Australasian 2k WG is moving forward following a workshop in 2005 and a resulting synthesis special issue. Joëlle Gergis presented a new temperature reconstruction for the region covering the last ~500 years, and highlighted new efforts to reconstruct regional temperature, precipitation and pressure using a suite of proxy records. This WG will now work towards extending the temporal and spatial coverage of time series, and reconstruction of the large-scale climate modes that drive climate in the region.

The Arctic 2k WG was launched in 2008 and has recently produced a compilation of temperature sensitive proxies from 23 sites around the Arctic. Darrell Kaufman highlighted this synthesis and demonstrated that temperatures in the 20th century reversed a millennial-scale cooling trend. Efforts are now being directed towards the development of additional proxy records, the inclusion of discontinuous timeseries and the reconstruction of the hydroclimatic variability of the region.

The Antarctic 2k effort is predominantly driven by the IPICS 2k project. Representing this group, Eric Steig outlined a number of recent reconstructions and modeling results for various climatic parameters. A data synthesis paper focusing on century-scale variability during the last 1 ka is currently in progress and several projects collecting 2 ka cores have recently begun.

Eugene Wahl gave a final presentation on the importance of contributing data to international databases, such as NOAA's World Data Center for Paleoclimatology. This is particularly pertinent for large-scale syntheses such as the 2k Regional Network. Eugene also outlined the variety of database tools available to researchers, and prompted discussion on ways to improve database usability and efficiency.

The 2k Network will produce a synthesis book, including chapters on each region and an overall global synthesis chapter. Each regional chapter will discuss the climate of a number of key periods (e.g., Medieval Climate Anomaly, Little Ice Age, Maunder Minimum), with the global signal and driving dynamical changes summarized in the global chapter.

Further details are available from the PAGES website (http://www.pages-igbp.org/science/focus2themes).

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For full references please consult:
www.pages-igbp.org/products/newsletters/ref2009_3.html

Young scientists meet to exchange science, network and learn about PAGES

PAGES 1st Young Scientists Meeting – Corvallis, USA, 6-7 July 2009

Pedro DiNezio[1], C. Cleroux[2], P. Applegate[3] and P. Collins[4] (YSM Participants)

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PAGES 1st Young Scientists Meeting (YSM) offered a platform for scientific exchange, networking and career development for more than 90 young scientists from 21 countries. The meeting also provided these young scientists with information about PAGES and other international global change organizations. The scientific program was organized around PAGES four scientific Foci; 1) Climate Forcings; 2) Regional Climate Dynamics; 3) Global Earth System Dynamics; and 4) Human-Climate-Ecosystem Interactions. In addition, several presentations were dedicated to three of PAGES four Cross-Cutting Themes (CCTs); 1) Chronology; 2) Proxy Development, Calibration and Validation; 3) Modeling.

Participants included mostly students in the later stages of their PhD and early-career PhD graduates, selected by a competitive application process. The participants contributed to oral and poster sessions, and participated in informal breakout groups and discussions. World-class senior scientists also participated in the meeting with special lectures. The first day started with a talk on the relevance of paleoclimate research by Nicklas Pisias (Oregon State University). He raised important questions on aspects of past climates that are relevant for issues of global warming, such as climate sensitivity to external forcing, and mechanisms of climate change and feedbacks.

Nick Pisias' presentation set the stage for the young scientists, who followed with their own talks. The talks covered cutting-edge topics in paleoclimatology, such as evaluation of mechanisms and tipping points using data and models, reconstruction of past and recent climates, exploration of assumptions made in the development of proxies, attribution of past climate changes, and modeling of past climates. A flavor of the range of research reported is given by the following (purely subjective) selection of presentations.

For PAGES Focus 1, Catalina González (University of Bremen) showed a reconstruction of rapid sea-level change associated with Heinrich events, using pollen ecology from a marine core. Her analysis of the ecological response of intertidal tropical ecosystems in the Cariaco Basin provides evidence on the timing of sea-level changes during MIS 3 and their connection with Heinrich Events, supporting the idea that sea level fluctuated along with Antarctic climate. Alberto Reyes (University of Alberta) presented a record documenting the response of permafrost to last interglacial warming. This study suggests that carbon sequestered in near-surface permafrost is likely highly vulnerable to 21st-century warming, however deeper permafrost and its associated carbon reservoirs are probably more stable than previously thought. Jeremy Shakun (Oregon State University) presented new insights on the sensitivity of the climate system to CO_2 forcing, based on an empirical orthogonal function analysis of all the available proxies of the last deglaciation. His analysis shows that proxies have a global temperature signal that is not correlated with ice sheet or insolation changes but is very well correlated with CO_2 forcing. The relationship between CO_2 forcing and global temperature suggests sensitivities to CO_2 forcing in the upper range of the IPCC models. Akitomo Yamamoto (Hokkaido University) showed in a 1-D numerical model that massive releases of methane from the sea floor get dissolved in the ocean instead of reaching the atmosphere, suggesting that deep-sea methane releases are unable to cause massive changes in atmospheric composition.

Under PAGES Focus 2, Martin Tingley (Harvard University) presented a Bayesian model assimilating incomplete (in space and time) instrumental and proxy data sets. He used this model to reconstruct, with uncertainties, 600 years of surface temperatures for high northern latitudes, based on tree ring, ice core, and lake sediment core data, confirming the unprecedented nature of 20th-century warming (Fig. 1). For PAGES Focus 3, Jessica Tierney (Brown University) presented evidence of centennial-scale changes in rainfall amount in southwest Indonesia during the last two millennia, based on hydrogen isotopic ratios on terrestrial higher plant leaf waxes ($\delta D_{leaf\ wax}$) in marine sediments. Under PAGES Focus 4, Megan Walsh (University of Oregon) discussed roles of natural environmental variability and human activity in shaping the fire and vegetation history of the Oregon region. Using charcoal and pollen analysis of lake sediments, she highlighted the variability in the drivers of fire history, from climate-driven vegetation shifts in some areas, to human-influenced regimes in others.

Several innovative studies were also presented for PAGES CCT 2. For example, Julie Ferguson (University of California Irvine) presented the first seasonal-resolution SST and seawater $\delta^{18}O$ records for the LGM outside the tropics, showing winter cooling of up to 2°C. Her results suggest that processes other than insolation controlled the seasonality of the SST response to glacial conditions. Branwen Williams (Ohio State University) presented a 100-year record of $\delta^{15}N$ from a coral in the western Pacific, suggesting a shoaling of the equatorial thermocline during the 20th century. The results from this study are very encouraging for understanding the ocean response to a weakening of the Walker circulation. Hopefully, more records of this type will help constrain our understanding of tropical climate change.

The afternoons were devoted to poster sessions. Modeling experiments over several time intervals that are useful for understanding the inner workings of the climate system, such as the LGM, the 8.2 ka event, the Eemian, and the last 2 millennia, were presented in both the poster sessions (Jung-Eun Lee, University of Chicago; Summer Rupper, Brigham Young University; Feng He, University of Wisconsin-Madison) and talks of CCT3 (Andreas Born, University of Bergen; Steven Phipps, University of New South Wales). In addition to this, results from numerical simulations of stable isotopes showed that calibration equations based on modern climate do not necessarily apply to past climates. Analysis of proxies also sheds light on limitations of typical assumptions, for instance, Caroline Cleroux (Lamont-Doherty Earth Observatory) presented revealing evidence for changes in calcification depth of the

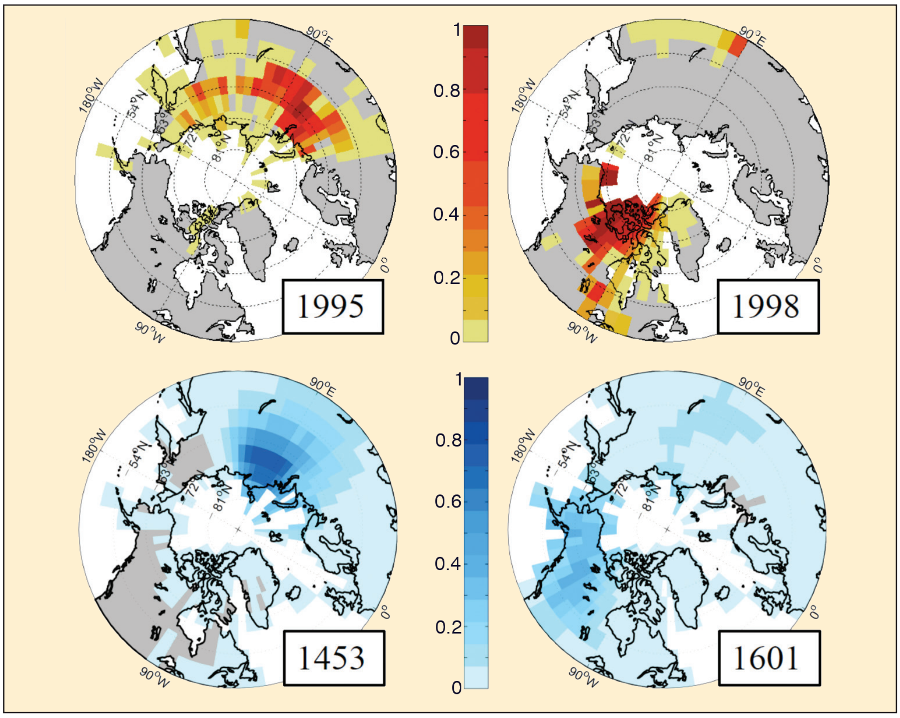

Figure 1: Warmest (top panel) and coldest (bottom panel) years in the Northern Hemisphere during the 1400-1999 period, estimated using a Bayesian methodology and proxy data (M. Tingley).

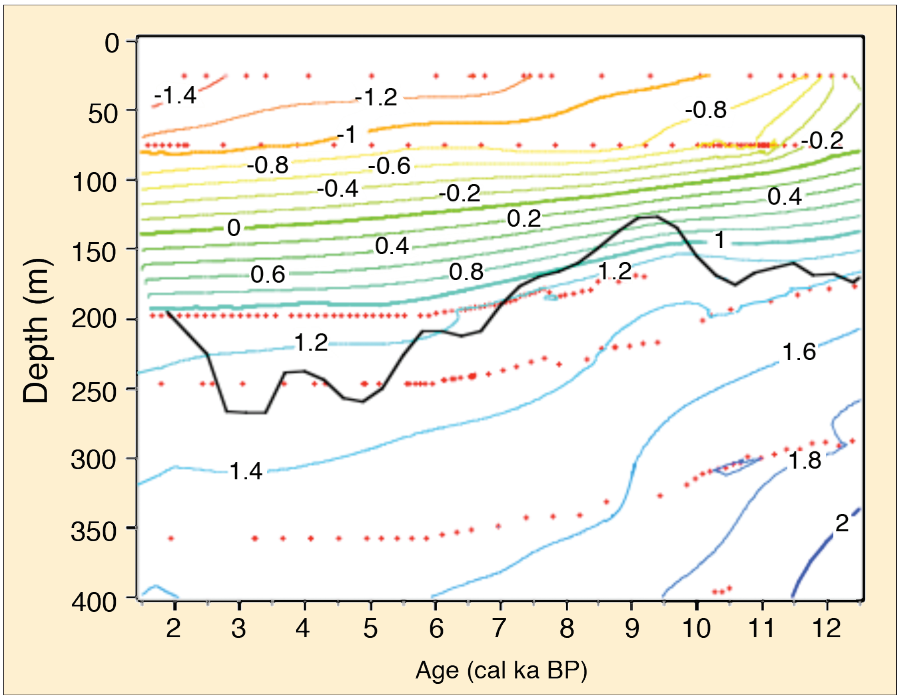

Figure 2: Calcification depth of the foraminifer Globorotalia truncatulinoides over the last 12.5 ka, calculated from $\delta^{18}O$ reconstructions from planktonic and benthic foraminifera in the Florida Straits (figure reproduced with permission from Cleroux et al., 2009).

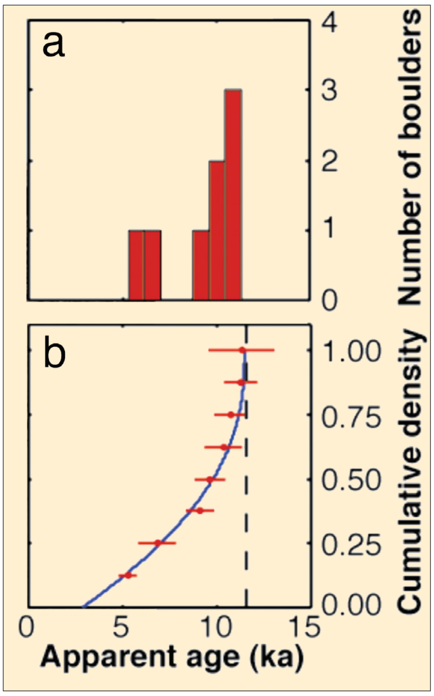

*Figure 3: Cosmogenic nuclide concentrations in moraine boulders indicate the ages of the moraines but the apparent moraine ages yielded by different boulders on the same moraine often differ by thousands of years (**a**; Barrows et al., 2007). Geomorphic process modeling can help determine the age of a moraine from a highly scattered data set (**b**; Applegate et al., 2008).*

foraminifer *Globorotalia truncatulinoides* between deglaciation and the Holocene. Her study emphasizes the need for better understanding of the ecology, life cycle, and controls on calcification depth for *G. truncatulinoides* and other planktonic foraminifera that are used to reconstruct the history of the thermocline and upper water column structure (Fig. 2). More assumptions typically used in the study of past climate were challenged in the poster session. Thomas Laepple (Alfred Wegener Institute) presented work that suggests that some climate records may be more strongly predicted by local insolation than insolation at high northern latitudes, after the seasonality of those climate records is taken into account. Pedro DiNezio (University of Miami) exposed the limitations of analogs, such as El Niño, to understanding tropical climate change. Patrick Applegate (Pennsylvania State University) presented numerical models of cosmogenic nuclide accumulation in boulders on glacial landforms. These models are able to explain the wide statistical distributions of cosmogenic exposure dates from certain moraines (Fig. 3). Pamela Collins (École Polytechnique Fédérale de Lausanne) used a coupled model of soil genesis and vegetation to examine pollen records from around the Mediterranean. Her work suggests that agricultural soil degradation may have caused an observed shift in pollen types that was previously attributed to a large-scale drying (Fig. 4).

On the final day, a number of presentations were given with the aim of providing information on key aspects of a researcher's career. Paul Filmer, PAGES Program Manager from the US National Science Foundation, provided background on research funding structures in the US. He anticipates opportunities in abrupt climate change and the hydrological cycle due to interest of the funding agencies in understanding tipping points and in having comprehensive hydrologic projections. For those interested in proxy development, Dr. Filmer indicated that the Paleo Perspectives in Climate Change (P2C2) program emphasizes producing climate data to test models, and gaining insight into mechanisms and rates of change. Dr. Prabir Dastidar from the Indian Ministry of Earth Sciences then addressed the Plenum with a brief account of a developing country's perspective on science funding.

This valuable information was complemented by the presentation of Alicia Newton (Associate Editor of Nature Geoscience), who provided insight into what high-impact journals expect. She emphasized that scientific results need to be clear conceptual advances in their fields to have a chance for publication in journals like *Nature* or *Science*. In addition to this, she reminded young scientists that aside from data and conclusions, clarity is very important. Thorsten Kiefer, from the EGU journal *Climate of the Past*, then introduced the relatively novel concept of open-access publishing and public, transparent peer-review.

David Anderson from NOAA's Paleoclimatology Program discussed issues of data management and explained that NOAA is interested in paleoclimatology to improve our understanding of decadal variability, extend the instrumental record into the past, and understand abrupt climate change.

To conclude, Gavin Schmidt from NASA/GISS presented important issues that arise when science is communicated to non-scientists. He recommended avoiding scientific discussions where scientific method is not followed. Additionally, he reminded us that scientists have a responsibility to avoid sensationalism and over-extrapolated conclusions from their work. He advised to state the implications of new work carefully, without overselling the results, and explicitly stating what the results do not mean when press releases are made.

The YSM successfully bridged the gap between summer schools and conferences by providing a relaxing environment to learn from colleagues from other fields. Simultaneously, it facilitated networking between emerging young scientists and introduced them to organizational aspects of science, such as funding, publishing, and communication of results. The concept behind this meeting worked efficiently to support the young scientists on their initial steps toward advancing the field of paleoclimatology.

Note

For more information on the figures here, and the talks and posters presented at the YSM please visit http://www.pages-osm.org/ysm/.

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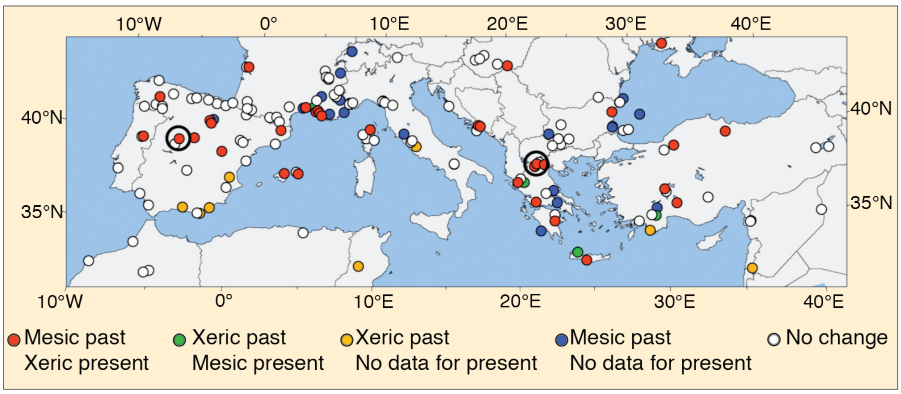

Figure 4: Map of the analyzed pollen-based biomizations for 6ka and present day from sites throughout the Mediterranean; red circles indicate those sites that currently support xeric (adapted to dry habitats) vegetation but that contained mesic (requiring moderate water) biomes at 6ka (P. Collins).

PAGES 3rd Open Science Meeting: Retrospective views on our planet's future

T. Kiefer, L. Newman and L. Witton

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Following the PAGES Open Science Meetings (OSMs) in London (1998) and Beijing (2005), PAGES held its 3rd OSM in the northwestern USA. Over 4 days in early July, the town of Corvallis, Oregon, was overrun by 300 scientists from 6 continents and 30 countries with a broad interest in past climatic and environmental changes. Under the meeting theme of "Retrospective views on our planet's future", paleoscience of various shades was presented and discussed at extensive poster sessions, plenary sessions, and (presumably) during social side events. The program included (i) poster and oral sessions structured along the focus elements of PAGES new Science Plan, (ii) "hot topic" discussions on such subjects as the role of paleoscience in IPCC, past ocean acidification, Sahara drying, and abrupt sea level rise, and (iii) a public lecture given by Jim Hansen on "Global warming time bomb: The path from science to action".

Beyond the cutting edge science that was presented, the OSM was a milestone for PAGES in several ways. For the first time, all the talks were recorded and can be viewed online or ordered gratis on DVD. It was also the first time an OSM was held in conjunction with a Young Scientists Meeting, and the first time a PAGES soccer championship was played (resulting in a glorious win for the modelers over the proxies team).

Another innovation launched at the OSM was the PAGES "Paleodata Portal". This single, coordinated search engine was created together with PANGAEA (Network for Geoscientific and Environmental Data) and the NOAA World Data Center for Paleoclimatology, with the aim to speed up and simplify searches for relevant paleodata. A test version of the Portal is now online at http://www.pages-igbp.org/dataportal. During the current trial stage, the Portal is harvesting metadata sets from PANGAEA and NOAA WDC. In the next phase, PAGES will invite other data centers and smaller thematic databases to join the initiative.

Alongside the scientific program, lunchtime chats and a plenary discussion on future directions for past global change science provided invaluable feedback on the direction and operation of paleoscience in general, and for PAGES in particular. With regard to the scope and organization of PAGES science, there was agreement that there needs to be stronger involvement of modern process scientists, such as climate dynamicists, to achieve a more detailed process understanding of how the Earth System operates. Moreover, strong arguments were made that the focus on paleoecological characteristics of global change should be expanded in order to more directly contribute to such aspects of societal relevance. In terms of products, the community emphasized that PAGES should support synthesis of data and model results as a valuable basis for understanding climate and environmental processes, and to feed into assessments such as those of the IPCC. A longer-term vision expressed was the idea to raise a multi-national pool of money (similar to the way IODP operates) in order to fund research on key questions in past global change science in an internationally coordinated manner. Such large-scale funding would allow the urgent questions to be answered more quickly and concertedly.

With regard to organizational aspects of PAGES, it became clear that the activities of PAGES and opportunities for participation need to be communicated more effectively. So, we might shed some of our caution in spamming you with emails, and send e-news and updates more regularly. We will also explore the use of new internet media. A desire was also voiced for more clarity on how to get involved in PAGES, and how to contribute ideas for workshops and working groups. A stronger formalization of proposal processes was a concrete suggestion that will now be implemented.

Encouraged by the flood of enthusiastic feedback, PAGES is planning to hold its 4th OSM and 2nd YSM in 2013.

Further information

- Online poster exhibition: http://www.pages-osm.org/osm/abstracts/posters.html
- Program and videos: http://www.pages-osm.org/osm/videos.html
- Young Scientists Meeting: http://www.pages-osm.org/ysm/
- Paleodata Portal: http://www.pages-igbp.org/dataportal

Tales from the "Football" Field

PAGES Soccer Cup: Model *skill* triumphs over Proxy *error*!

Two highly qualified teams of YSM/OSM participants, F.C. Modelers and F.C. Proxies, went head to head in the first ever PAGES Soccer Cup. Despite considerable *uncertainty*, the match was eventually *well-resolved*. Richard Alley (Pennsylvania State University) scored the 1st goal for the Modelers. Jonathan Barichivich (University of East Anglia) evened the score for the Proxies *forcing* the game into extra time. The Modelers finally secured their *historical* victory with a goal by César Pérez Valdivia (University of Regina)!

Teams now have until 2013 to prepare for their next encounter at PAGES 4th OSM.

New on the PAGES Bookshelf

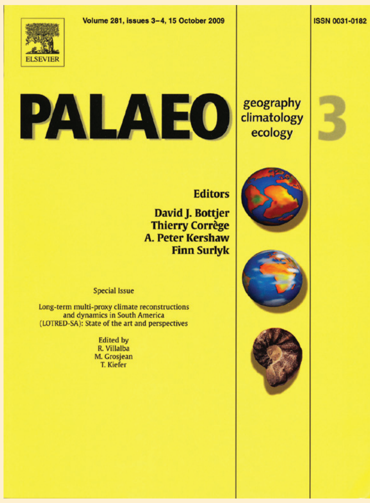
Long-term multi-proxy climate reconstructions and dynamics in South America (LOTRED-SA): State of the art and perspectives

Editors: R. Villalba, M. Grosjean and T. Kiefer

This special issue of *Paleo*[3] stems from the PAGES LOTRED-SA Working Group and provides a state-of-the-art overview of regional climate variations and reconstructions in South America over the last millennia.

Summary of Contents:

- Editorial
  R. Villalba et al.
- Present-day South American climate
  R.D. Garreaud et al.
- Documentary sources from South America: Potential for climate reconstruction
  M. del Rosario Prieto and R. García Herrera
- Dendroclimatological reconstructions in South America
  J.A. Boninsegna et al.
- Climate variability during the last 1 ka inferred from Andean ice cores
  F. Vimeux et al.
- Glacier fluctuations in extratropical South America during the past 1ka
  M.H. Masiokas et al.
- Fluctuations of glaciers in the tropical Andes over the last 1 ka & palaeoclimatic implications
  V. Jomelli et al.
- Reviewing human–environment interactions during the past 3 ka
  M. Morales, et al.
- Spatio-temporal variations in *P. tarapacana* radial growth across the Bolivian Altiplano
  C. Soliz et al.
- ENSO signal in the world's highest-elevation tree-ring chronologies, Altiplano, Central Andes
  D.A. Christie et al.
- Climate signals in high elevation tree-rings from the semiarid Andes of north-central Chile
  J. Barichivich et al.
- Long-term glacier variations from historical records & tree-ring reconstructed precipitation
  C. Le Quesne et al.
- LIA glacier advance in the Central Andes, Argentina
  L.E. Espizua and P. Pitte
- LIA fluctuations of small glaciers in the south Patagonian Andes, Argentina
  M.H. Masiokas et al.
- Palaeoenvironmental changes during the last 1.6 ka inferred from a cirque lake in Patagonia
  M. Fey et al.



For more information, see special issues in PAGES Product Database: http://www.pages-igbp.org/products/

Contents

Announcements

- Inside PAGES 90
- Eulogy - John Eddy 90
- PAGES calendar 91
- New on the PAGES Bookshelf 135
- Tales from the "football" Field 135

Special Section: Advances in Paleolimnology

- Editorial: Advances in Paleolimnology 92

Science Highlights:

- The potential of high-resolution X-ray fluorescence core scanning 93
  P. Francus, H. Lamb, T. Nakagawa, M. Marshall, E. Brown and Suigetsu Project Members
- The potential of varves in high-resolution paleolimnological studies 96
  A. Brauer, P. Dulski, C. Mangili, J. Mingram and J. Liu
- FTIRS: Rapid, quantitative analysis of biogeochemical properties of lake sediments 98
  P. Rosén, H. Vogel, L. Cunningham, N. Reuss, D. Conley and P. Persson
- Stable isotopes in chitinous fossils of aquatic invertebrates 100
  O. Heiri, M.J. Wooller, M. van Hardenbroek and Y.V. Wang
- Microbial membrane lipids in lake sediments as a paleothermometer 102
  J.W.H. Weijers, C.I. Blaga, J.P. Werne and J.S. Sinninghe Damsté
- Ancient DNA in lake sediment records 104
  M.J.L. Coolen and J.A.E. Gibson
- Tracking the effects of "aquatic osteoporosis" using paleolimnology 106
  A. Jeziorski, A.M. Paterson, N.D. Yan and J.P. Smol
- Calibration-in-time: From biogeochem. proxies to quantitative climate variables 108
  M. Grosjean, L. von Gunten, M. Trachsel and C. Kamenik
- Environmental and climatic changes inferred from lake deposits in China 110
  P. Rioual and L. Wang
- Paleolimnology of African lakes: Beyond the exploration phase 112
  D. Verschuren and J.M. Russell
- South American lake paleo-records across the Pampean Region 115
  F. García-Rodríguez, E. Piovano, L. del Puerto, H. Inda, S. Stutz, R. Bracco, D. Panario, F. Córdoba, F. Sylvestre and D. Ariztegui
- Results of recent sediment drilling activities in deep crater lakes 117
  R. Pienitz, M. Melles and B. Zolitschka

Program News:

- Paleolimnology and the restoration of aquatic systems 119
  P. Gell, H. Bennion and R. Battarbee

Program News

- The PAGES/CLIVAR Intersection: Vision for the future 121

Science Highlights: Open Section

- Younger Dryas *Larix* in eastern Siberia: A migrant or survivor? 122
  P. Tarasov, S. Müller, A. Andreev, K. Werner and B. Diekmann

Workshop Reports

- Holocene Climate Change in the Asian Region 124
- The East African Quaternary: Lessons from the past for the future 124
- Data-assimilation techniques for paleoclimate data 125
- Peatland archives of Holocene climate variability 127
- Climate variability, forcings, feedbacks and responses 128
- Mechanisms of Quaternary climate change: Stability of warm phases 129
- Towards a global synthesis of the climate of the last 2 ka 130
- PAGES 1st Young Scientists Meeting 131
- PAGES 3rd OSM: Retrospective views on our planet's future 134

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