



Invited review

Varves in lake sediments – a review

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ABSTRACT

Downcore counting of laminations in varved sediments offers a direct and incremental dating technique for high-resolution climatic and environmental archives with at least annual and sometimes even seasonal resolution. The pioneering definition of varves by De Geer (1912) had been restricted to rhythmically deposited proglacial clays. One century later the meaning of 'varve' has been expanded to include all annually deposited laminae in terrestrial and marine settings. Under favourable basin configurations and environmental conditions, limnic varves are formed due to seasonality of depositional processes from the lake's water column and/or transport from the catchment area. Subsequent to deposition of topmost laminae, the physical preservation of the accumulating varved sequence requires the sustained absence of sediment mixing, for example via wave action or macrobenthic bioturbation. Individual (sub) laminae in varved lake sediments typically express contrasting colours, always differ in terms of their organic, chemical and/or mineralogical compositions, and often also differ with regard to grain-size. Various predominating climatic and depositional conditions may result in clastic, biogenic or endogenic (incl. evaporitic) varved sediments and their mixtures.

To reliably establish a varve chronology, the annual character of laminations needs to be determined and verified in a multidisciplinary fashion. Sources and influences of possible errors in varve chronologies are best determined and constrained by repeated varve counts, and by including radioisotopes and correlation with historically documented events. A well-established varve chronology greatly enhances the scientific value of laminated limnic archives by securely anchoring the wealth of multi-proxy palaeoenvironmental information in the form of time-series for multidisciplinary investigations.

Applications of varved records are discussed with special reference to advances since the 1980s. These span fields like calibrating radiometric dating methods, reconstructing past changes of the Earth's magnetic field or detecting fluctuations in solar forcing. Once a varve chronology is established it can be applied to precisely date events like volcanic ash layers, earthquakes or human impact, as well as short- and long-term climate (temperature, precipitation, wind, hydroclimatic conditions or flooding) and environmental changes (eutrophication, pollution). Due to their exceptional high temporal resolution and in combination with their robust and accurate "internal" time scale in calendar years, annually laminated sediments can be regarded as one of the most precious environmental archives on the continents. These records are necessary to extend temporally limited instrumental records back in time. As such they have societal relevance with regard to risk assessments related to natural hazards arising from e.g. flooding or volcanic eruptions.

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1. Introduction

Concerns about global climate change and its effects on nature and human activities, including economic, social and political affairs, are exerting pressure on science to produce models and predictions for future climate trends and variabilities. Knowledge of the timing and magnitude of past environmental and climatic

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changes can assist in such predictions. Although available instrumental meteorological data are pointing towards past climatic variations, instrumental time-series are rarely continuous, typically cover less than two centuries and lack global coverage. Therefore, addressing the important millennial-scale climate variability requires greatly enhanced data coverage both geographically and through time (Bradley, 2014). Written, historical reports about weather phenomena, crop failures or floods are occasionally preserved, mostly for the last millennium, but their fragmentary nature and reliance on the subjectivity of chroniclers limit their value for quantitative palaeoenvironmental reconstructions. In consequence of these limitations, reconstructions over longer timescales mainly rely on indirect proxy information from natural archives. In the continental realm, lacustrine sediments offer depositional archives where sedimentation has been affected by past temperatures, precipitation, volcanism, solar activity, biomass burning, pollution and other factors. Some lacustrine records from non-glaciated areas extend back in time beyond the Last Glacial Maximum (Zolitschka et al., 2000; Brauer et al., 2007a,b; Shanahan et al., 2008; Bronk Ramsey et al., 2012; Melles et al., 2012; Neugebauer et al., 2014; Stockhecke et al., 2014), while the majority of records pertains to higher latitudes or mountainous altitudes providing continuous records with high temporal resolution for the Holocene (Fig. 1). Altogether, these lacustrine records reflect palaeoenvironmental conditions and can be analysed with sedimentological, geochemical, geophysical and biological techniques summarised as palaeolimnology or limnogeology (Berglund, 1986; Last and Smol, 2001; Cohen, 2003). As the formation of lacustrine sediments is dominantly controlled by climatic processes and by catchment geology, the analysed sediment properties, so-called “palaeoclimate proxy data” (often abbreviated as “proxies”), can be used as indicators of the variability of past environmental

conditions as well as of the impact of human influences on lake systems and their catchment areas (Fig. 2). The transport of material from the catchment to the lacustrine environment is dependent on the climatically controlled hydrology. Climate and geology jointly control the formation of soils and plant cover in the catchment, and together with the open or closed nature of a lake, i.e. with or without outflow, they also control water chemistry and plankton communities (Wetzel, 2001). As geology does not change significantly throughout the life span of lacustrine basins, variations recorded in lakes and their sediments are predominantly related to climate variability. Numerous lake catchments and their hydrologic settings in industrialised countries have witnessed strong anthropogenic impacts during the last ca 150 years. Intensified land use and increased nutrient-rich runoff into lakes can trigger oxygen depletion of lake water that strongly affects the structure and composition of accumulating sediment (e.g. Wehrli et al., 1997).

The deposition of sediment incorporates environmental information as proxies relating to sedimentary structure and composition. Each sedimentary column represents a palaeoenvironmental archive that requires a measure of depositional age (i.e. a chronostratigraphy) to yield meaningful time-series of their proxies. Unlike the trunk of a tree growing over time by adding distinct layers of organic matter (tree rings) comparable to successive pages of a book, most lake sediments appear to be massive without any obvious structure that can be assigned to reflect an internal chronology beyond the trend of sediments getting progressively younger towards the top. However, under certain conditions lacustrine sediment can accumulate and be preserved as a succession of laminae representing a seasonal cycle of sedimentation that is often driven by annual climate variability. The recognition of such annually laminated (i.e. varved) lake sediments more than 150

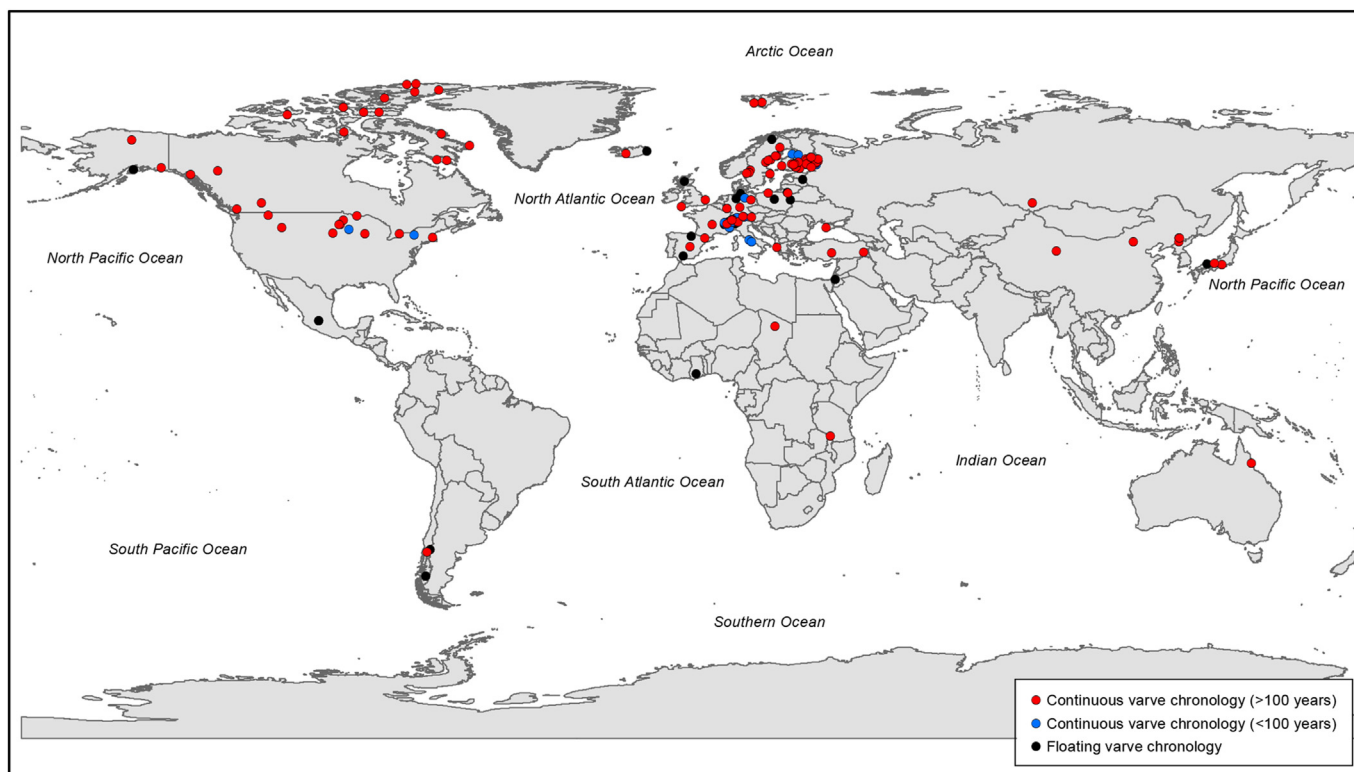


Fig. 1. Worldwide distribution of 143 published and peer-reviewed lacustrine varved Holocene and Pleistocene sediment records (cf. e-component 2, Supplementary data). Note that many varved sites are not shown if they are unpublished or incompletely described in terms of varve chronology or varve model and components.

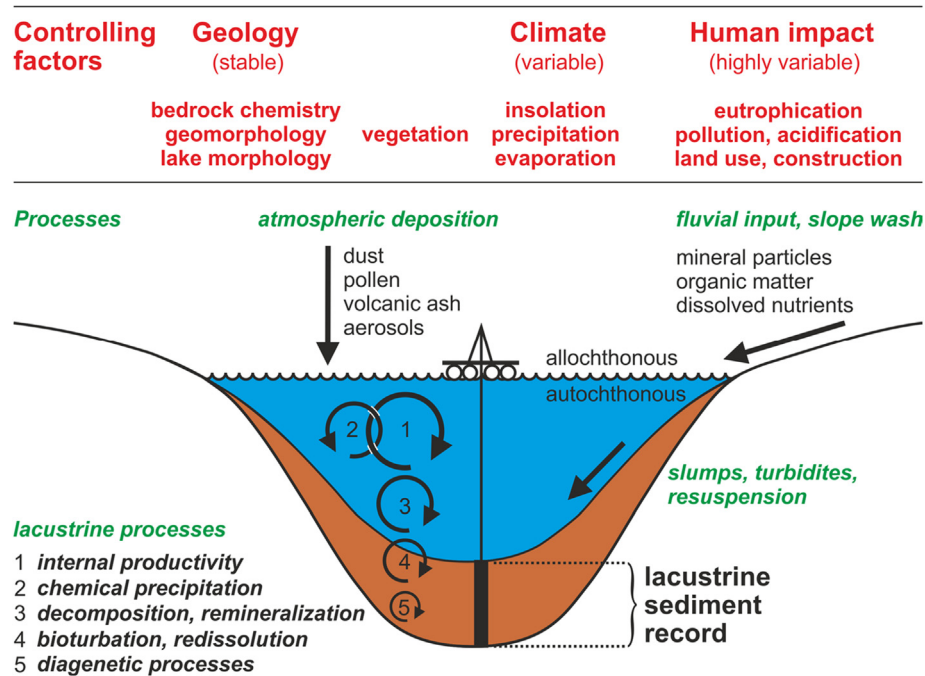


Fig. 2. Formation of lacustrine varved sediments: controlling factors and processes (modified after Zolitschka and Enters, 2009).

years ago was a milestone in geology and triggered intensive research, much of which predated our pressing concern about global climate and environmental change: “Nature vibrates with rhythms, climatic and diastrophic, those finding stratigraphic expression ranging in period from the rapid oscillation of surface waters, recorded in ripple-mark, to those long-deferred stirrings of the deep imprisoned titans which have divided earth history into periods and eras. The flight of time is measured by the weaving of composite rhythms — day and night, calm and storm, summer and winter, birth and death — such as these are sensed in the brief life of man. (...) We must seek out, then, the nature of those longer rhythms whose very existence was unknown until man by the light of science sought to understand the earth. The larger of these must be measured in terms of the smaller, and the smaller must be measured in terms of years. Sedimentation is controlled by them, and the stratigraphic series constitutes a record, written on tablets of stone, of these lesser and greater waves of change which have pulsed through geologic time” (Barrell, 1917: 746). Varved sediment records are the records measured in terms of years. They are now appreciated as invaluable sources of information for quantitative palaeoclimate reconstruction (e.g. Larocque-Tobler et al., 2015), to track ecosystem responses to climate change (e.g. Randsalu-Wendrup et al., 2012), to assess human impact over time (e.g. Lotter and Birks, 1997), to determine recurrence intervals of volcanic eruptions (Van Daele et al., 2014) and flood events (Czymzyk et al., 2013; Corella et al., 2014) for regional hazard assessments and, most of all, to enable precise dating on an absolute calendar-year time scale (e.g. Nakagawa et al., 2012).

Earliest reviews on varved sediments more than 30 years ago (Saarnisto, 1979a; O’Sullivan, 1983) were followed by more regional overviews (Anderson et al., 1985; Boyle, 1993; Mörner, 2014) and reviews in books with limited distribution (Saarnisto, 1986; Zolitschka, 2003, 2007; Brauer, 2004; Hughen and Zolitschka, 2007; Saarnisto and Ojala, 2009). In light of many new methodological developments and applications over the past few years, it is timely to provide an updated review on varved lacustrine sediments and their relationship to cutting-edge sedimentary and environmental research. This paper strives to facilitate comprehensive and

DOI-supported access to relevant gateway literature for students and scientists. We outline a strategy to survey lakes with varved sediments and explain various basic types of varves forming under different climatic and environmental conditions. The scope of this review does not permit detailed coverage of the large and complex variety of varves encountered in lakes in extreme environments. Instead, we provide electronic links to the online “[Varve Image Portal](#)” visualising examples of seasonal sedimentary successions, as well as specific sediment components and peculiar sedimentary structures (cf. [Supplementary data as e-components](#) to this publication). We also review established techniques to develop a coherent varve chronology, as well as best practices to obtain records of sedimentation and variations in accumulation rates to leverage complementary proxy analyses. Finally, examples of the latest advances in analytical approaches on varved records are presented.

There are several topics that lie outside the scope of this review. First, we do not include varved records from beyond the last glacial (ca 50 ka), although older lacustrine varves have been reported. For example, it is known that some earlier interglacial deposits are composed of comparable varved structures like those recorded today (e.g. Mangili et al., 2007; Koutsodendris et al., 2011). In deep time, finely laminated sediments reflect earlier stages in atmospheric and biological evolution and thus are composed differently than today (cf. Anderson and Dean, 1988 as an introduction). Our article also does not cover marine varves (Kemp, 1996 as an introduction), a topic reserved for an upcoming review (Schimmelmann et al., Submitted for publication). In the meantime, a search for the key word ‘marine’ in the extensive “[Varves Literature Archive](#)” points to ca 400 relevant records from the marine realm. This literature archive currently hosts more than 1600 publications on all varve-related aspects worldwide from lacustrine and marine realms.

2. History

Annually laminated sediments were first documented in 1862 as “*hvarfig lera*” (Swedish for cyclic layer) by the Swedish Geological

Survey on one of the first geological maps of Sweden to describe rhythmically-deposited clays in a proglacial environment. Initially the term 'varved sediments' was used synonymously for annually laminated proglacial lake deposits, often also called varved clays. At about the same time when Swedish geologists mapped varved clays, Heer (1865) interpreted alternating pale and dark laminated non-glacial sediments in Swiss outcrops as a potential source of chronological information. However, half a century passed before these early observations were developed into a concept for the first dating tool in geology. In the early 20th century, the Swedish geologist Gerard De Geer used the term *varve* to define one complete annual depositional cycle consisting of a coarse-grained pale summer layer and a fine-grained dark winter layer in varved clay sequences. In addition, he coined the term 'geochronology' and pioneered the meaningful use of the temporal unit 'year' in geological sciences (De Geer, 1908), which was distinctly different from the qualitative stratigraphic classification commonly used at that time. De Geer systematically applied the chronological information stored in varved clays deposited near the margin of the retreating Scandinavian Ice Sheet to date the deglaciation and the termination of the Pleistocene epoch. Moreover, he established a network of varved clay sites along the Baltic coast of Sweden and cross-correlated these records using varve characteristics and relative thickness variations (De Geer, 1912). The approach was soon applied successfully to varve sequences in Finland by Matti Sauramo (1923). Varves quickly gained international recognition as a powerful concept with its rapid adaptation in glacial (Reeds, 1926) and non-glacial lake sediments (Whittaker, 1922; Perfiliev, 1929). The synergetic exploitation of accurately dated varve records followed in combination with instrumental meteorological records (Schostakowitsch, 1936) as well as fruitful applications in palaeomagnetism (McNish and Johnson, 1938) and palynology (Welten, 1944).

De Geer was convinced that solar forcing had controlled varve thickness in Swedish clay sequences through the modulation of melt-water discharge (De Geer, 1926). Consequently he and his colleagues attempted to cross-correlate Swedish varve thickness records with those from Finland (Matti Sauramo), North America (Ernst Antevs), Patagonia (Carl Caldenius) and central Asia (Erik Norin) to provide evidence for a global solar signature in coeval varve thickness records (De Geer, 1937). However, the presumed long-distance correlations (teleconnections) were discredited by many scientists at that time who regarded varve chronologies to be a subjective and unreliable dating tool. The generally negative attitude towards varves as a geochronological tool intensified after Willard Libby invented the radiocarbon dating method in 1949. Ironically, after fundamental limits to the accuracy of radiocarbon dating have become obvious since the 1980s, it is now well established that decadal or even centennial accuracy of ^{14}C -ages for periods with fluctuating cosmogenic ^{14}C production in the atmosphere is unlikely. Dendrochronology combined with ^{14}C -AMS (accelerator mass spectrometry) dating of annual wood growth-rings has been the method of choice to construct a calibration curve for radiocarbon dates across much of the Holocene. However, subfossil trees are rare or absent for the Lateglacial and beyond, and thus annually laminated lake sediments have regained their importance for longer-term calibration of radiocarbon ages (Wohlfarth et al., 1995; Kitagawa and van der Plicht, 1998; Goslar et al., 2000; Hajdas et al., 2000; Bronk Ramsey et al., 2012).

A renaissance of applied varve research during the 1970s was prompted by the growing awareness of human environmental impacts on watersheds and freshwater supplies in lakes and reservoirs that were affected by eutrophication, acidification, pollution and soil erosion. Proper assessment of problematic sites

required well-dated and high-resolution information about the past to extend typically short instrumental records for environmental monitoring. It was especially important to establish comparative natural background levels characterizing the environmental conditions prior to the onset of severe anthropogenic disturbances. Spurred on by newly developed coring techniques (e.g. freeze corer, piston corer) and more sophisticated analytical tools, varved lake records came into focus for applied environmental research targeting predominantly non-glacial laminated lake sediments (e.g. Ludlam, 1969; Renberg, 1976, 1981a; Simola, 1977; Sturm, 1979; Saarnisto, 1979a,b; Anderson et al., 1985). The term *varve*, which so far had been restricted to proglacial environments, was finally extended to all annually laminated sediment records not only on continents (O'Sullivan, 1983; Saarnisto, 1986) but also in marine settings (Kemp, 1996). Marine sedimentologists had adopted the term 'varve' even much earlier for annually laminated and non-glacial marine deposits (Seibold, 1958; Calvert, 1966; Olausson and Olsson, 1969) and since the 1980s have discovered several varved sites where marine bottom waters are sufficiently depleted in oxygen to exclude bioturbation (Baumgartner et al., 1985; Anderson et al., 1987; Behl and Kenneth, 1996; Hughen et al., 1996; Kemp, 1996; Schulz et al., 1996).

Today the terms 'varved' and 'annually laminated' are considered synonyms. Occasionally the expression 'classic varves' is still used for proglacial clay varves related to glacier retreat to distinguish them from non-glacial varves.

3. Composition, formation, preservation and definition of varves

3.1. Composition of varves

Based on a genetic concept, lacustrine sediments can be compositionally categorised as clastic, biogenic and endogenic. (1) Clastic (i.e. detrital, minerogenic) sediment receives a flux of siliciclastic particles from external sources either through fluvial activity, slope wash or via atmospheric deposition (aeolian dust, volcanic ash). (2) Biogenic sediment results from biological production of organic matter and biomineralisation (some organisms build inorganic skeletons made of biogenic silica (opal) or carbonates) in the water column of a lake and in the catchment area. After the death of organisms, their biomass is typically passed through the so-called microbial loop where most organic matter is metabolically oxidised, i.e. 'remineralised'. Only a small, refractory portion of organic matter becomes incorporated in the accumulating sediment where it is subject to ongoing biodegradation and early diagenesis. All aerobic and dysaerobic heterotrophic degradation of organic matter in lakes depletes dissolved oxygen in the lake water. (3) Endogenic (minerogenic) sediments receive crystallizing particulate material via chemical precipitation of minerals from the water column during its supersaturation that is often, but not always, linked to evaporation. Precipitation of typical endogenic minerals, such as calcite, gypsum or halite, depends on the solubility product and concentrations of participating ions in aqueous solution.

An alternative approach classifies lacustrine sediments according to their origin as autochthonous (i.e. produced within the lake from lacustrine productivity or via precipitation) or as allochthonous (i.e. transported into the lake from the catchment area or beyond). Although the environmental conditions necessary for the formation of clastic, biogenic and endogenic or autochthonous and allochthonous components are clearly constrained, the vast majority of lacustrine sediments are mixtures of these components or mixed domain varves (Anderson and Dean, 1988).

3.2. Controls on the formation of varves

Relative contributions of the various autochthonous and allochthonous components to a lacustrine sedimentary record typically vary through time and are controlled via catchment geology, prevailing climatic conditions and more recently by human influence (Fig. 2). Geologic factors can explain differences between lakes with contrasting geological catchments. However, the geology of a single site is generally stable and does not modify depositional processes during the lifetime of a lake. A notable exception from this rule relates to the isolation of a lake basin from the world ocean because of postglacial isostatic uplift. Due to the absence of vegetation in the catchment area and the littoral zone, these lacustrine basins were prone to more substantial erosion causing elevated and variable mineral matter sedimentation for hundreds or even thousands of years after their isolation. Establishing vegetation eventually stabilised the system and increased the biogenic content of sedimentary varves (e.g. Ojala and Alenius, 2005; Valpola and Ojala, 2006). Climatic influences, in contrast, are variable over longer timescales. Decadal, centennial and millennial fluctuations were moderate for the Holocene (e.g. Wanner et al., 2008), while more pronounced astronomical variations caused glacial and interglacial conditions that governed the pre-Holocene climate.

During the Holocene, climate exerted the main control on the development of soils and vegetation in lake catchments influencing the amount of runoff, the release of soluble elements such as nutrients and the availability and transport of minerogenic particles from the watershed towards the lake. This climatically-induced temperature changes and nutrient availability in lake systems resulted in variations in autochthonous biological activity.

More recent human impacts have amplified natural processes especially via changes in land use and destabilisation of catchment areas by deforestation (e.g. Zolitschka et al., 2003), thus enhancing the release of nutrients (cultural eutrophication) and minerogenic particles (soil erosion). Pollution by heavy metals (e.g. Renberg et al., 1994; Schettler and Romer, 1998) and lake acidification (e.g. Facher and Schmidt, 1996) are additional consequences of more recent human activities affecting lacustrine depositional systems.

Seasonal climatic differences are more pronounced than most long-term climatic variations, especially outside of the tropics. Temperature and precipitation are responsible for the seasonal succession of lacustrine and terrestrial life forms as well as for physical and chemical processes within lakes and their catchment areas. Processes in the watershed control autochthonous biological productivity and the precipitation of endogenic minerals by transferring dissolved (i.e. nutrients) and particulate minerogenic and organic matter from the catchment area to the lake (Fig. 2). Seasonal forcing translates to a seasonal succession of sedimentary characteristics (i) if seasonally variable runoff translates into erosion and transport of allochthonous (minerogenic) components into the lake, (ii) if the concentration of certain dissolved ions (e.g. calcium, carbonate, iron, sulphate) vary throughout the year and occasionally exceed the solubility product of endogenic minerals, and/or (iii) if lacustrine productivity is high enough to produce distinct algal blooms under mesotrophic to eutrophic conditions. A seasonally variable and significant flux of different components to the sedimentary record is a necessary precondition for the formation of annually laminated sediments.

3.3. Preservation of varves

The depositional signal of seasonally alternating fluxes of sedimentary components can result in varve patterns only in the

absence of post-depositional erosion, re-suspension, re-deposition and mixing in the sediment column. *In situ* mixing is mainly caused by bioturbation, but can also be caused by seismic liquefaction forcing lower-density fluids upwards as well as by bubbling of gases from below. Gravity-induced sediment relocation as well as wave- and current-induced sediment winnowing and re-deposition can cause large-scale mixing in unconsolidated sediments (Larsen and MacDonald, 1993). Especially in shallow lakes but also in the littoral zone of deep lakes, wind-related currents and waves may cause re-suspension, followed by down slope transport and re-deposition. For this reason deep lakes are preferred targets for high-resolution sedimentary studies. However, deep lakes often feature steep slopes and may be prone to gravity-induced slumping of sediment and turbidity currents. Both types of mass wasting commonly originate from an erosional base and deposit their sedimentary load when the slope diminishes towards the lake's depocentre where the flow loses momentum. Therefore, if the central deep lake basin is rather flat and extensive, erosional as well as depositional influences of slumps and turbidity currents are restricted to the slopes and outer fringes of the deep plain. The depositional modification of profundal sediments by slumps and hyperpycnal turbidity currents is negligible or recognisable (Sauerbrey et al., 2013).

The most important mechanism of sediment mixing in lakes is bioturbation, i.e. the burrowing and crawling activity of macrobenthic organisms like fish, molluscs, crustaceans and worms. Deeper lakes experience limited bioturbation because they tend to be stratified and therefore bottom waters are more likely to be depleted in dissolved oxygen due to microbial oxidation of organic matter. As the water column becomes stratified with regard to its concentration of dissolved oxygen, the epilimnion distinguishes itself from the hypolimnion by chemical stratification. Oxygen consumption in the hypolimnion can cause seasonally suboxic to anoxic conditions during summer and winter while in autumn and spring oxygen may be temporarily replenished during mixing of the entire water column (holomixis in a dimictic lake; e.g. Wetzel, 2001). Highly productive (hypertrophic) or very deep lakes might even develop an anoxic hypolimnion stable enough to be excluded from annual water circulation. Anoxia to suboxia exclude or limit the benthic presence of larger animals while still permitting adapted meiofauna, microfauna, microbes and fungi to partake in early diagenetic transformation of organic matter while not compromising the integrity of the varve structure. This is the case for deep, relatively small and wind-protected lakes (O'Sullivan, 1983; Ojala et al., 2000) favouring either continuously anoxic (meromictic) or seasonally suboxic to anoxic (dimictic) conditions in lake bottom waters.

A more effective enhancement of water-column stratification is afforded by chemical differentiation of the epilimnion from the hypolimnion (i.e. chemical stratification) that translates into the density of lake water. For example, a deep, perennial and anoxic water body (meromictic conditions) with a long residence time may contain dissolved salts that increase the density of the hypolimnion and further stabilise the stratification and anoxic conditions (Anderson et al., 1985). In some instances meromixis develops in lakes close to sea-level due to the presence of fossil saline or brackish water, or to temporary connections to the ocean during high tides or storms (e.g. Bradley et al., 1996; Besonen et al., 2008). In other cases anoxic conditions trigger microbial methanogenesis in organic-rich sediment and ebullition of methane gas-bubbles that can disturb the appearance of varves and their seasonal laminae. In summary, best conditions for the preservation of annually laminated sediments are found in eutrophic lakes with a low surface area/depth ratio and at least seasonal anoxic conditions in the hypolimnion.

3.4. Definition of varves

Climatic conditions can produce sets of seasonally contrasting and characteristic laminae over the course of one year not only at midlatitudinal and polar sites, but also in some subtropical and tropical regions (Fig. 1; Ojala et al., 2012). Here we provide a general definition of annually laminated sediments to clarify and harmonise the usage of the term ‘varve’.

All varve types contain at least two or more seasonal laminae with distinctly contrasting colour, composition, texture, structure and/or thickness. The succession of seasonally deposited layers reflects a repetitive annual cycle with site-specific characteristics. The depositional cycle of annually laminated sediments typically does not follow the course of calendar years, i.e. from January through December, but instead may be in tune with hydrological years, for example controlling clastic varve input from October through September. Alternatively, the depositional cycle may be governed by the phaeological cycle modulating the input for biogenic varves from spring to next year's winter. Varved records are not the result of a continuous and slow accumulation of particles. Instead, the details of varved records are controlled by a succession of depositional events representing pulses from runoff events (e.g. snowmelt and rainfall), algal blooms or periods of intense calcite precipitation, so-called whittings (e.g. Stockhecke et al., 2012). In spite of the stochastic nature of the magnitude and timing of some depositional phenomena, the overall varve record remains subject to the overriding seasonal climatic control. Given the dating uncertainties discussed below, the stochastic variations can be regarded as negligible and the term “calendar-year chronology” is typically justified. To better understand the formation of different types of varves and associated climatic and limnogeological conditions, their appearances are introduced in the following sections.

3.4.1. Clastic varves

Clastic sediments in lakes predominate under cold climatic conditions such as polar and alpine regions and are typical of proglacial and periglacial lakes (Fig. 3). Intensive physical weathering related to gelifraction and the lack of vegetation make large quantities of minerogenic matter available that is easily eroded and transported into lakes. Sediment transfer is closely linked to the annual freeze–thaw cycle and to the amount of snowmelt-related runoff in these environments (Hardy et al., 1996; Cockburn and Lamoureux, 2008) or to a combination of snow- and glacier-melt in proglacial environments (Ridge et al., 2012). In addition to melt water runoff, precipitation can produce secondary runoff events throughout the summer (Lapointe et al., 2012). As chemical weathering and plant growth are limited, lakes in cold regions are poor in nutrients (oligotrophic) and dominated by minerogenic sediments.

Clastic varves are formed when seasonal runoff carrying suspended sediment enters a lake with a stratified water body (Sturm, 1979). According to its density and in relation to the density of the lake water column (which is mainly controlled by water temperature), the inflowing sediment-laden stream water is positioned in the lake as over-, inter- or underflow (Smith and Ashley, 1985; Francus et al., 2008). Over- and interflows cause a wide distribution of suspended matter across the entire lake while underflows are more prone to generate turbidity deposits closer to the river-mouth area. After entering the lake, the flow velocity of the stream water is transformed into turbulence reducing its capacity. Accordingly, coarser particles (sand, coarse silt) are deposited immediately at the point of river inflow forming sediment bodies such as deltas, whereas fine silt and clay remain in suspension for longer periods and are distributed across the lake. In colder climates, clay particles may remain in suspension until the lake is covered by ice during the following winter, when turbulence is completely inhibited and fine-grained clay layers are (clay cap) deposited. Thus, clastic varves are typically composed of both a coarse-grained lower and a fine-grained upper lamina (Fig. 3). Additional coarse-grained laminations are occasionally observed and can be related either to successive snowmelt events, e.g. cold spells interrupting the ongoing snowmelt, or to rainfall events during the relatively short open-water period in summer (Ringberg and Erlström, 1999; Cockburn and Lamoureux, 2008). Therefore, in these environments, the presence of a distinct clay cap is the main criteria for identifying a year of sedimentation.

3.4.2. Biogenic varves

Under temperate climatic conditions the catchment area is vegetated on well-developed soils that limit the availability and transport of minerogenic particles into the lake. Chemical weathering produces fine-grained (clay) minerals and releases nutrients from the parent material which become available to plants in the catchment area. Decaying organic matter from litter or soil can be transported as particulate detritus or as dissolved organic matter (e.g. humic and fulvic acids) into the lacustrine system. At the same time, the leaching of dissolved nutrients (e.g. nitrate, ammonium and phosphate) from the catchment and their drainage into lake water can result in eutrophic conditions of the lake. These productive lakes are prone to form and preserve biogenic varves (i.e. organic varves) reflecting the cycle of annual organic productivity (Fig. 4). The related increase in organic productivity draws down the availability of dissolved oxygen in the hypolimnion whereby previously dimictic lakes can become meromictic or at least oxygen-depleted during summer and start forming and preserving varves (e.g. Wehrli et al., 1997).

Nutrients are transferred from the hypolimnion to the photic zone during mixing of the lake's entire water body (holomixis) in

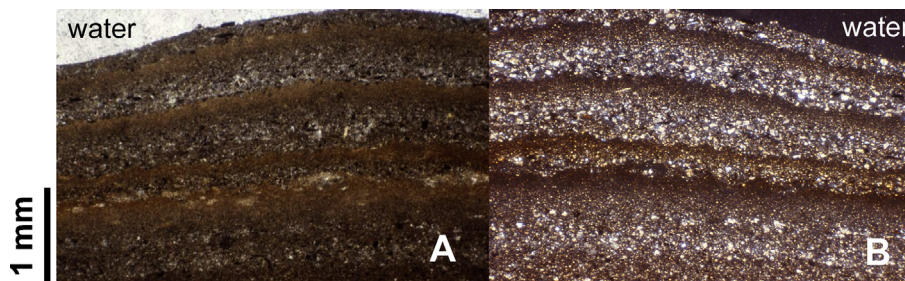


Fig. 3. Clastic varves near the sediment/water interface of Lake C2, north coast of Ellesmere Island in the Canadian High Arctic. The microscopic photograph of non-glacial clastic varves documents the undulating sediment–water interface in (A) normal light and (B) polarised light. Pale and coarse-grained laminations are related to snowmelt runoff during summer. In contrast, dark and fine-grained laminations result from particles settling out of suspension during ice cover in winter (modified after Zolitschka, 1996).

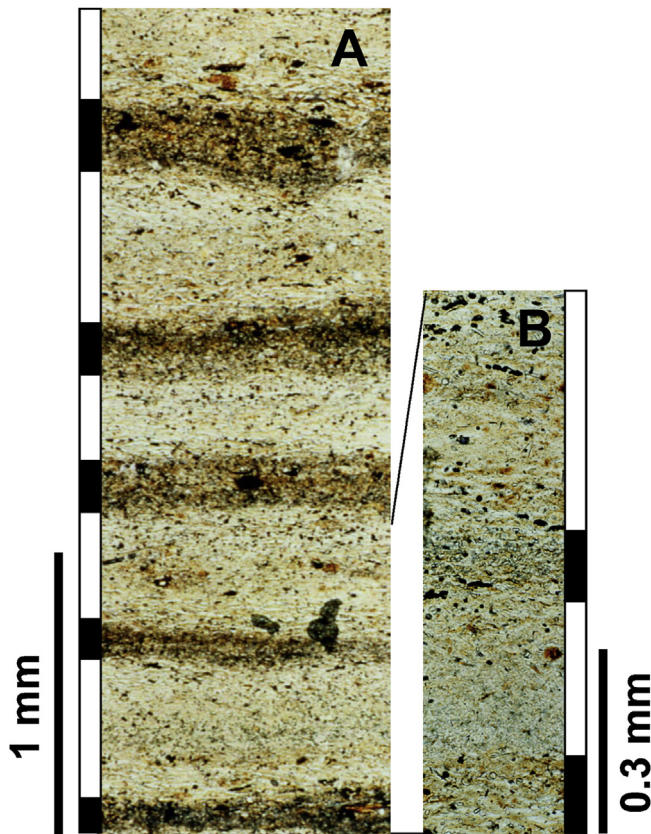


Fig. 4. Mid-Holocene biogenic varves from Lake Holzmaar in Germany (Zolitschka et al., 2000). (A) Macroscopic photograph of pale diatom laminae and dark organic detritus. (B) Microscopic photograph in normal light documents the internal structure of biogenic varves. Massive planktonic diatom blooms produce pale laminae, whereas dark laminae contain larger benthic and epiphytic diatoms as well as dark spots of organic matter and pyrite. The black and white bars on the left or right of the images indicate the dark and pale sublaminae of annual layers (also for some subsequent figures; Photographs by Bernd Zolitschka).

late winter or early spring. This triggers algal blooms at a time of rising temperatures and increasing insolation. Diatom blooms in early spring may be followed by blooms of green and blue-green algae during summer. Sometimes autumnal mixis produces a second diatom bloom. The *post-mortem* decomposition of green and blue-green algae yields few structural fossils whereas siliceous diatom frustules are well preserved and prominent microfossils in lacustrine sedimentary records (Smol and Stoermer, 2010) except under alkaline conditions where biogenic silica is dissolved (Reimer et al., 2009).

Concluding the annual biogenic varve cycle during fall and winter, the final lamina consists of plant detritus and minerogenic components that can be interspersed with metal sulphides. Under anoxic conditions, dissolved sulphate is microbially reduced to sulphide that precipitates in the presence of some metals, most prominently iron to eventually form pyrite (FeS_2). The precipitation of authigenic metal sulphides can occur *in situ* in the uppermost varves near the sediment/water interface where the redox gradient from suboxic bottom water to anoxic pore water is strong. Diminished plant cover during winter renders soil vulnerable to erosion. Runoff events related to winter rain or rainfall-triggered snowmelt transport minerogenic matter as well as littoral and terrestrial organic matter into the lake. Depending on the amount of runoff, this lamina can be distinctly developed and typically varies considerably through time.

3.4.3. Endogenic varves

Endogenic (including evaporitic) minerals originate from the water column by chemical precipitation that can be biologically and physically induced (Last, 2001). These minerals should not be confused with authigenic minerals formed by diagenetic transformation after sedimentation such as pyrite (FeS_2), siderite (FeCO_3) or vivianite ($\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$). The most frequent biologically induced endogenic mineral is calcite (CaCO_3). Varves with endogenic calcite are mostly found in mixed varve types (see below). Physically induced endogenic minerals are plentiful. For instance, manganese and iron containing precipitates are formed in the water column when the seasonal circulation (especially in autumn) oxygenates the hypolimnion (Nuhfer et al., 1993) and also occur mainly in mixed varve settings. Endogenic varves are often evaporitic. Strong evaporation of lake water, e.g. under arid or semiarid climatic conditions, increases salinity and may alter the pH. The deposition of evaporitic varves is triggered as soon as the solubility product of a specific mineral compound (e.g. salts) is exceeded. Calcite can precipitate physico-chemically under semi-arid to arid climatic conditions (e.g. Gac et al., 1977). Evaporitic varves may also contain aragonite (CaCO_3), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) or halite (NaCl) and are typically composed of pale-dark couplets (Fig. 5). The pale lamina is attributed to salt precipitated during the dry summer whereas the dark lamina is related to runoff events introducing a mixture of minerogenic grains and organic detritus during colder and moister winters. Evaporitic laminae can also be found alternating with wind-blown silt and sand laminae (Francus et al., 2013a).

3.4.4. Mixed varves

The three different types of clastic, biogenic and endogenic varves rarely exist as pure end members. Perhaps clastic varves are the only type that can exist without significant biogenic and endogenic components. Organic varves often contain runoff-related minerogenic contributions deposited during winter or spring depending largely on factors like catchment geology and the existence of surficial inflow, the occurrence of fine-grained clastic sediments in the catchment area and strong seasonally contrasting precipitation. In Scandinavia the resulting mixed varve type is widely known as clastic-biogenic (or clastic-organic) and typically contains a characteristic minerogenic lamina linked to snowmelt during spring (Renberg, 1981a; Zillén et al., 2003; Ojala and Alenius, 2005; Ojala et al., 2005; Fig. 6). It depends on the dominating component whether the sedimentary structure is attributed to a more minerogenic (clastic-biogenic) or a more biogenic (biogenic-clastic) varve type, as transitions are not always clearly distinguishable. Endogenic varves also coexist with runoff-related minerogenic laminae. For example, clastic-endogenic varves have been described for Lake Van in Turkey (Stockhecke et al., 2012, 2014) and from the Dead Sea in Israel and Jordan (Fig. 5; Neugebauer et al., 2014).

Certain geological settings allow biogenic varves to contain endogenic minerogenic components. If limestone or calcareous particles in unconsolidated till or loess in the catchment area are dissolved through weathering and soil formation, lakes can be saturated with calcium carbonate even under temperate climatic conditions. Calcite precipitates if the concentrations of Ca^{2+} and CO_3^{2-} ions exceed the solubility product of calcium carbonate. This can partly be achieved by a seasonal temperature increase in surface waters because CaCO_3 becomes less soluble with increasing temperature. However, more important is the temperature-related increase of photosynthetic activity in the water column. As aquatic photosynthesis is withdrawing CO_2 and bicarbonate from the water, the pH increases to 9 and reduces the solubility of CaCO_3 . This combination of increasing temperature with biological activity

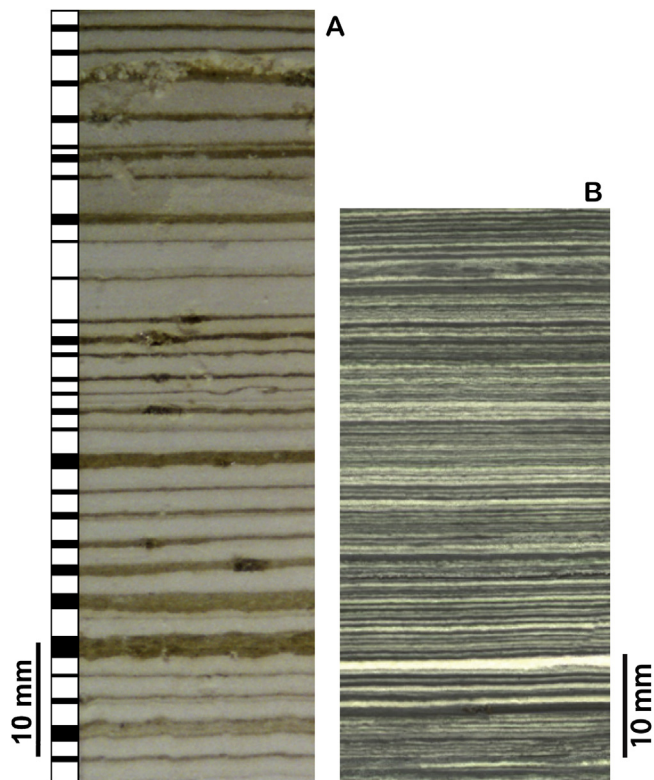


Fig. 5. Endogenic (evaporitic) varves (A) from the Late Pleistocene palaeo-Dead Sea (Lisan Formation; photograph by Moti Stein) and (B) from 105.8 m below the lake floor (ICDP Dead Sea Deep Drilling Project; modified from Neugebauer et al., 2014), both Israel. The annual cycles are composed of alternating pale aragonite laminae precipitated during arid summers and dark laminae consisting of allochthonous organic and clastic matter from winter flood events. Both records date to the Last Glacial Maximum and comprise proximal (A) and distal (B) facies.

during late spring and early summer can add a well-defined whitish carbonate layer as an endogenic component to organic varves (Fig. 7) and result in a varve type best described as carbonaceous or carbonaceous-biogenic (Dean and Megard, 1993).

Ferrogenic (i.e. iron-rich) varves are also a mixed biogenic varve type with an endogenic minerogenic component (Anthony, 1977; Renberg, 1981a). They are mostly found in the boreal climatic zone (Brauer, 2004) and develop in non-carbonaceous softwater lakes rich in soluble iron (Fe^{2+}) where redox changes related to the dimictic nature of these lakes control the seasonal precipitation of less soluble, oxidised iron (Fe^{3+}). Decomposition of organic matter during periods of stagnation (summer, winter) causes anoxic conditions where iron is reduced to its soluble form. Following holomixis in spring and autumn, iron is oxidised and precipitates as pale brown layers of ferric hydroxides which later and at a certain depth can be converted to authigenic pyrite during early diagenesis.

Siderite (FeCO_3) is commonly regarded as an early diagenetic product and present as scattered crystals or lenticular bodies that can form siderite laminae (Mingram, 1998). Such siderite-enriched laminae can be diagnosed only microscopically. However, this iron carbonate can also precipitate from the water column in some iron-rich lakes with alkaline pH. This occurs if calcium and sulphide cations are limited and CO_2 is available via anaerobic decomposition of organic matter (Anthony, 1977; Bahrig, 1989) providing evidence of an anoxic-nonsulphidic-methanic environment according to Berner (1981).

Our categorization of varves has been guided by the concept that processes related to varve formation are controlled by the prevailing climate. In principle this is true, but climatic and environmental conditions vary over the course of a year and therefore favour the deposition of mixed varve types. Mixed varve types are common not only spatially among sites and climatic zones but are also regularly observed over depth and time at individual sites (Brauer, 2004). For instance, sites in central Europe, such as Holzmaar, may initially preserve non-glacial clastic varves during the termination of the Weichselian glaciation, succeeded by carbonaceous organic varves,

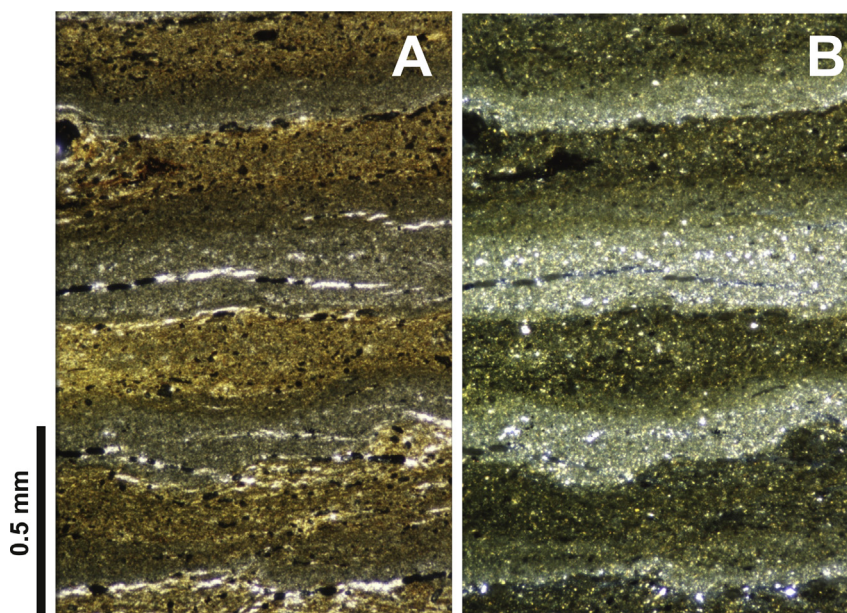


Fig. 6. Clastic-biogenic (mixed) varves from Alimmainen Savijärvi in Finland dated to 8150 cal BP (Ojala et al., 2000). The base of the annual cycle is formed by allochthonous minerogenic matter from spring snowmelt discharge. Autochthonous organic matter is accumulated during the rest of the year. Organic matter in brown hues under normal light (A) turns dark under polarised light (B). Photographs by Antti Ojala.

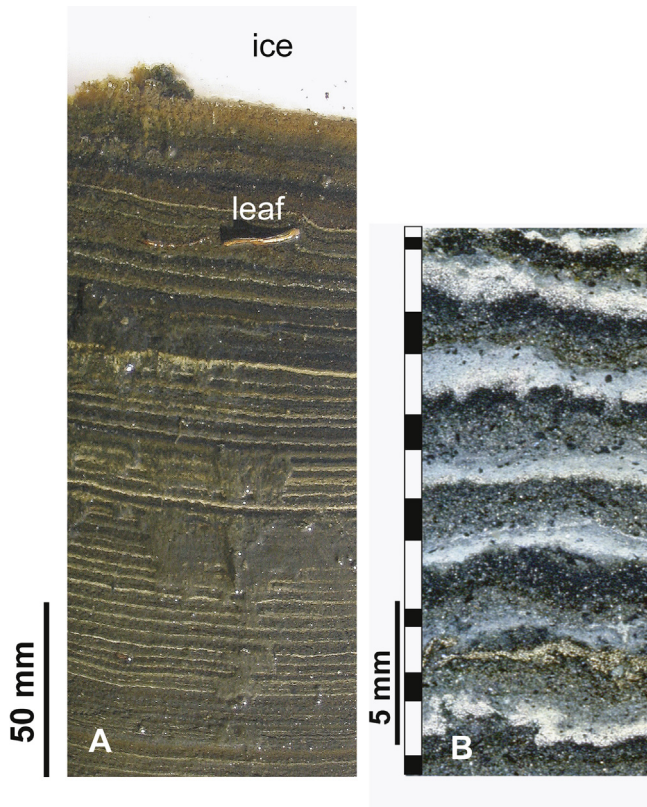


Fig. 7. Calcareous-biogenic varves from Sacrower See in Germany (Lüder et al., 2006; Bluszcz et al., 2009). (A) Macroscopic photograph of freeze core. A well-preserved sediment–water interface marks the top of a succession of calcareous organic varves with pale calcite laminae. (B) Microscopic photograph in polarised light documents the internal structure of varves from the 20th century. Each annual cycle of three sub-laminae consists of (i) almost black lamina from spring planktonic diatom blooms, (ii) white calcite summer laminae, and (iii) grayish detrital wintertime layers with black stains. Photographs by Philipp Bluszcz (A) and Dirk Enters (B).

then organic varves without carbonates during the course of the Holocene, and more recently by clastic-organic varves after the human impact accelerated soil erosion over the last three millennia (Zolitschka et al., 2000). In the end, fluctuations among different varve types within a single basin provide information about the climatic and environmental conditions of their formation.

4. Distribution of varved records

In the 1980's, the worldwide geographic distribution of 60 varved lakes reported by O'Sullivan (1983) is strongly biased in favour of the European Alps, northern Sweden and Finland, north-eastern North America and the East African Rift System. In a recent inventory of 143 well-documented lacustrine varve chronologies (Fig. 1) from all over the world - the updated Varves Data Base (VDB, cf. supplementary data; updated from Ojala et al., 2012) – documents a more evenly distributed global availability of varved lake records. Based on field surveys and sediment coring, Sweden alone boasts ca 100 (Pettersson, 1996), Finland more than 50 (Ojala et al., 2000), and northeast Poland 24 varved lakes (Tylmann et al., 2013a) that have not yet been thoroughly studied. Despite this geographic bias significant progress has been made in other regions with a large number of lakes during the last two decades, for example in Japan (Fukusawa, 1999) and China (e.g. Chu et al., 2012).

The discovery of most varved sedimentary records in the past occurred in the myriad of lakes across recently deglaciated terrains (Fig. 1) and initially occurred by chance, whereas more recent

findings have been guided by empirical considerations such as water depth and meromictic conditions (cf. O'Sullivan, 1983; Anderson et al., 1985). Several surveys came to the conclusion that annually laminated sediments are commonly found in lakes with water depths exceeding 10 m (Saarnisto, 1986; Ojala et al., 2000) and rarely occur between 5 m and 7 m (Ojala et al., 2000; Zillén et al., 2003).

Based on maximum water depth ($Z_{\max}$) and lake surface area (A), Hutchinson (1957) developed 'relative depth' (Z_r) as an integrated morphometric parameter that was used by O'Sullivan (1983) to characterise lakes with varved records. Z_r expresses $Z_{\max}$ as the percentage of the mean diameter of a lake:

$$Z_r = 50Z_{\max} \sqrt{\pi} / \sqrt{A} \quad (1)$$

Of the 57 lakes in O'Sullivan's (1983) study that provided a value for Z_r , 35.1% have Z_r values < 2% while deep lakes with small surface areas (40.4%) express $Z_r > 4\%$. Currently the updated VDB (cf. Supplementary data) features 143 lakes with varves that have been plotted with Z_r and $Z_{\max}$ against lake surface-area (Figs. 8 and 9). The relationship between $Z_{\max}$ and the area of lakes with varved records (Fig. 9) documents that $Z_{\max}$ generally increases with lake size. A few outliers are characterised by high salinities stabilising the stratification of the water column which explains why varves are preserved in spite of shallow water depths and large lake surfaces. After exclusion of the hydrologically unusual sites, the mean relative depth of the remaining lakes is $Z_r = 4.04\%$. Only 22.4% of the lakes with varved records express $Z_r < 2\%$ while 36.8% have values of $Z_r > 4\%$. In general, the distributions of O'Sullivan's dataset and the more extensive updated VDB are comparable (cf. Fig. 4 of O'Sullivan (1983) with Fig. 8 in this review) and document that smaller lakes require enhanced relative depths to preserve varved sediments. The major difference between both datasets is that the updated VDB associates the majority (40.8%) of varved records with a Z_r between 2% and 4% whereas the dataset of O'Sullivan (1983) proposes only 24.5% for this group.

Based on the same morphological lake parameters, Larsen and MacDonald (1993) developed a heuristic approach to predict whether a lake develops laminated or massive sediments. Physical models and empirical data from 159 lakes from the USA and Canada were used to develop a parameter describing the critical boundary depth (Z_m) between lakes with either massive or laminated sediments as a function of lake surface area (A in ha):

$$Z_{m_l} = 7.78 A^{0.294} \quad (2)$$

A high potential for the preservation of laminated sediments is indicated when a lake has a maximum depth in excess of Z_{m_l} (Larsen and MacDonald, 1993). However, a re-examination of this approach on an extended data set of 297 lakes shows that Equation (2) predicted only 18% of all laminated records correctly and therefore additional factors must control the formation and preservation of laminated sediments (Larsen et al., 1998). Thus, they modified their statistical approach demonstrating that non-laminated (massive) sediments mostly occur in lakes where the maximum depth is shallower than the critical maximum depth (Z_{m_m}):

$$Z_{m_m} = 3.0 A^{0.294} \quad (3)$$

The conclusion of Ojala et al. (2000) that shallow lakes can be excluded from the search for varved records has so far been supported by the data of the updated VDB. After exclusion of seven outliers, most of the remaining 136 varved lakes plot deeper than

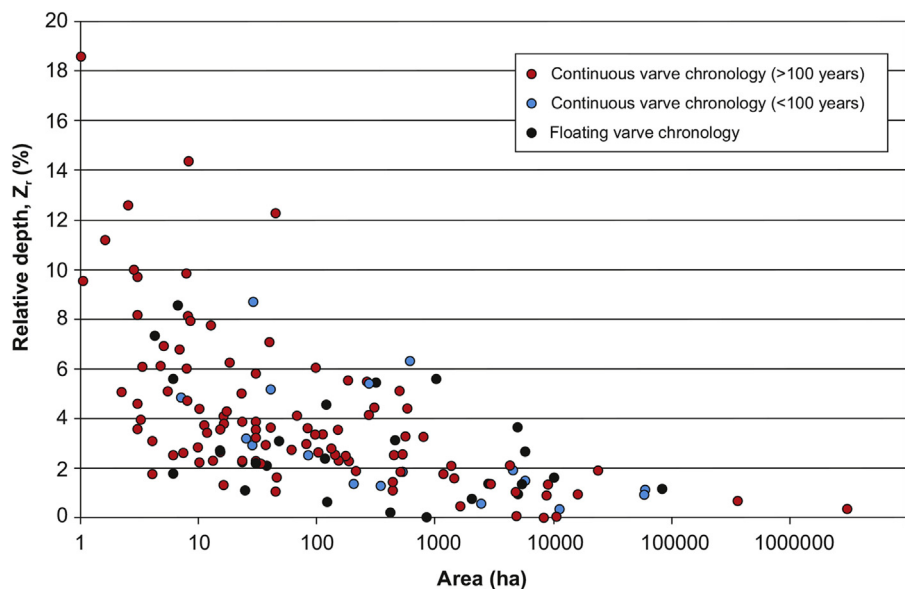


Fig. 8. Relationship of relative depth (Z_r) to logarithmic surface area for 143 lakes with published varved records listed in the updated Varve Data Base (e-component 2, Supplementary data).

their critical maximum depths (Z_{m_i}) as it was proposed by Larsen et al. (1998; Fig. 9).

The northeast Polish varve survey by Tylmann et al. (2013a) applied Equation (3) to pre-selected 60 small ($A < 300$ ha) and deep ($Z_{\max} > 15$ m) lakes with depths in excess of Z_{m_i} (Eq. (3)). Gravity coring revealed that only 24 of these lakes (40%) are laminated and only 19 out of these 24 lakes (31.7% of all selected or 79.2% of all laminated sites) are at least as deep as Z_{m_i} (Eq. (2)). Five lakes (20.8% of all laminated sites) with depths below Z_{m_i} (Eq. (2)) preserved topmost laminations only. This is most likely due to anthropogenic eutrophication causing a more stable stratification of the water column and thus better conditions for varve preservation. Lakes with massive sediments, however, were distributed equally below and above Z_{m_i} . These results confirm the importance

of additional factors, such as sedimentary flux to the lake, topographic exposure, shape of basins and geological characteristics in the catchment area for the formation and preservation of laminated sediments (Larsen et al., 1998; Ojala et al., 2000; Tylman et al., 2013).

The following variables were suggested by Tylmann et al. (2013a) to characterise the morphology of a certain lake basin when evaluating the potential to contain varved sediments:

- Mean wind fetch: mean distance between coring site and lake shore measured along 16 equally distributed compass directions;
- Maximum wind fetch: longest distance between coring site and lake shore as measured for mean wind fetch;

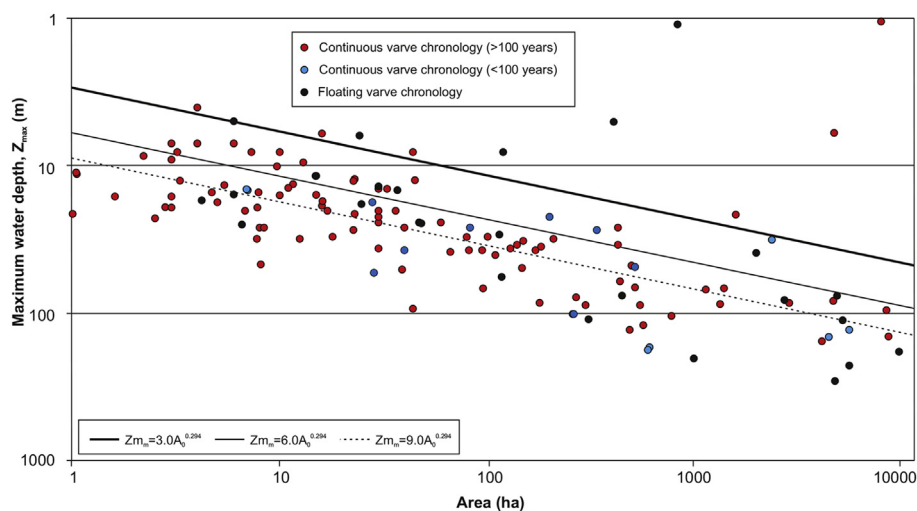


Fig. 9. Relationship of maximum lake water depth ($Z_{\max}$, on a logarithmic scale) to logarithmic surface area for 136 lakes with published varved records listed in the updated Varve Data Base (e-component 2, Supplementary data). Seven outliers with areas between 10,000 and 300,000 ha were excluded from this figure. Descending lines indicate critical depth vs. area (Z_{m_i}) according to Larsen et al. (1998). They determined a threshold separating laminated from massive sediments: all their 21 laminated records are below the line with an intercept of 3.0 and only homogeneous sediments occur above. Our study evaluates varved sites with 93% falling below the line with an intercept of 3.0. However, 7% of our varved records occur above this line.

- Topographic exposure: mean value for the maximum differences in elevation (i.e. maximum elevation minus elevation of the lake level) along a 500 m long line measured from the lake shore along 16 equally distributed compass directions;
- Exposure index: A/Z_{mean} , with lake surface area (A) in ha and mean depth (Z_{mean}) in m.

These parameters utilise the size and shape of the lake basin as well as the morphology of the immediate catchment area to identify likely sites for the deposition of laminated sediments. For instance, a low mean fetch/ Z_{max} ratio (<10) in combination with a high topographic exposure (>10) yields a success rate of 70% for the predicted occurrence of varved sediments in northeast Polish lakes (Tylmann et al., 2013a). Sites with a relatively recent onset of laminations are characterised by a low degree of sheltering from wind (topographic exposure <10). Wind-driven ventilation provides oxygen for macrobenthos and adds a non-morphological factor that can play a pivotal role for the preservation of laminations (Tylmann et al., 2013a). The relatively recent onset of laminations in numerous lakes over the last ca 150 years coincides with the development of agriculture and industry in populated areas of Europe and North America. The resulting cultural eutrophication often tipped the balance towards seasonal or longer-term anoxia in bottom waters (e.g. Wehrli et al., 1997; Lüder et al., 2006) that satisfied a critical precondition for the preservation of laminations, as exemplified by the record of Lake Greifensee in Switzerland (Wan et al., 1987; Fig. 10). The appearance of varves along a depth transect (cf. Fig. 11) can be used to reconstruct the history of anoxia within a lake basin (Jenny et al., 2013).

In summary, laminated sediments are more likely to be found in relatively deep lakes with small surface areas than in shallow lakes with large surface areas (Saarnisto, 1986; Larsen et al., 1998; Tylmann et al., 2013a). An ideal lake is deeply incised into the catchment area, surrounded by elevated terrain and forests restricting the influence of wind-driven mixing. These conditions can foster a seasonal stratified (dimictic) or even a permanently stratified (meromictic) water column with a lack in oxygen in the bottom water. Lake Suminko in northern Poland serves as an example (Tylmann et al., 2012) and documents that continuously laminated sediments are restricted to the deepest and oxygen-free part of the water column, the monimolimnion (Fig. 11). In the shallower part of the lake basin where the chemocline impinges the slope the sediments become discontinuously laminated, and at the level of the mixolimnion the sediments are homogenous (Fig. 11).

An ideal basin for the formation and preservation of varved sediments is additionally characterised by a lacustrine depth profile with a relatively flat depositional centre, a relatively high rate of sedimentation and stable slopes to avoid slumping and turbiditic sedimentation. Additionally, many Fennoscandian lakes have depocentres located close to the inflow of rivers and receive allochthonous minerogenic matter as an important component for the formation of clastic-biogenic varves (Ojala et al., 2000). This is, however, not always the case as varved records are sometimes found in shallower basins protected from the direct influence of main tributaries (Francus et al., 2008).

The various parameters and equations (Larsen et al., 1998; Tylmann et al., 2013a) are useful tools to scout for varved lakes and to optimise the selection process prior to a field survey. However, the underlying theoretical and heuristic assumptions are based on limited sampling of geographically restricted areas. Therefore, they simplify complex relationships and cannot reliably predict the presence or absence of varved sediments. We can be certain that many sites with laminated sedimentary records are still awaiting discovery.



Fig. 10. Freeze core with ice above varved lake sediments from Greifensee in Switzerland (Wan et al., 1987). The upper 26 cm of varves display the history of cultural eutrophication exemplified by the formation of carbonaceous organic (mixed) varves since the 1930s. The lake was less productive below 26 cm sediment depth where bottom water was oxygenated, and consequently no dark organic laminae were preserved. Photograph by Mike Sturm.

5. Varves and dating

Varves, tree rings, ice cores, speleothems, corals and bivalve shells all have layered structures with distinct sequences of laminae or growth increments through time. As long as there is sufficient evidence for an annual rhythm of laminae in these natural archives, their chronological sequence can be exploited by consecutive layer counting. The availability of an absolute anchor, such as inclusion of the topmost varve representing the year of coring and enabling counting back through time, will yield a precise and continuous calendar-year chronology assigning an age to each depth interval of the continuously varved record. Even without an anchor point, a floating varve chronology still provides precise relative time control. The tight chronological precision afforded by varve counting is a major advantage over other dating techniques such as radiometric dating which are commonly applied to sediment records and rely on discrete sampling and interpolation.

This section introduces a variety of techniques to obtain a detailed, well-dated, and thoroughly documented varved sediment record. A more detailed overview on coring devices has been compiled by Glew et al. (2001). Our main focus is directed on best practices to investigate the annual character of laminated sediments and to establish a varve chronology with verification and

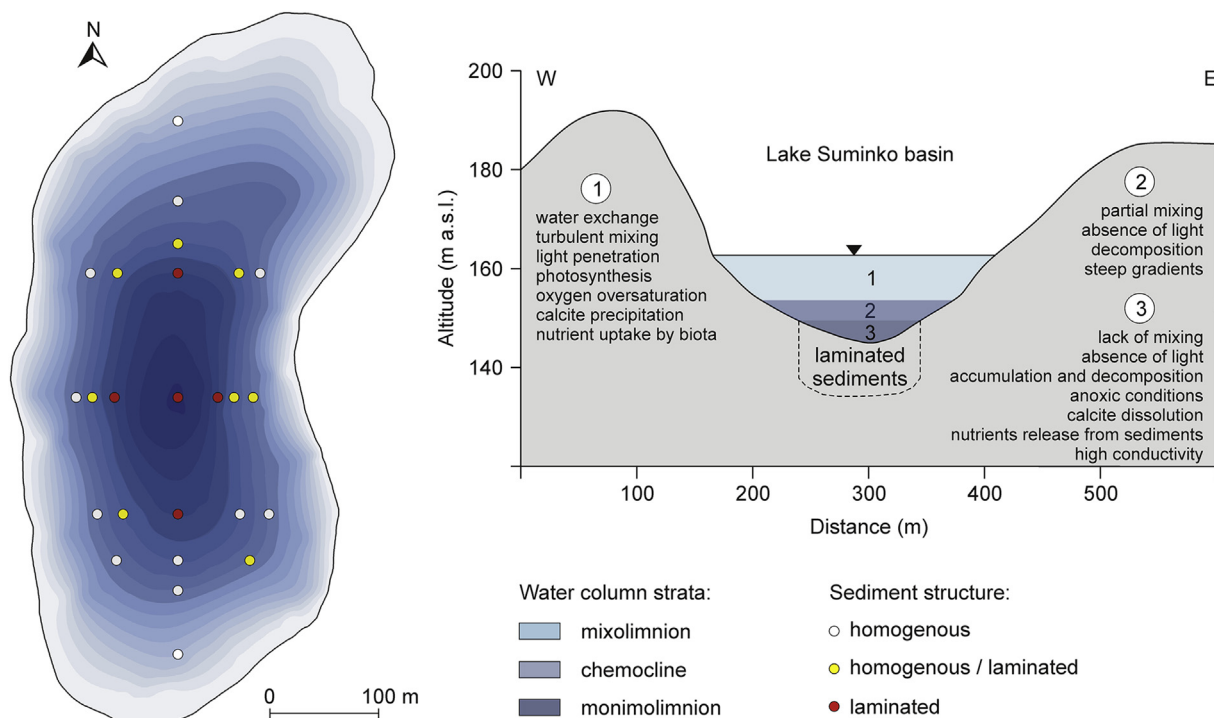


Fig. 11. Lateral extent and general conditions for the deposition of varved sediments in Lake Suminko, Poland. A meromictic type of stratification is described as (1) mixolimnion, (2) chemocline, and (3) monimolimnion (modified from Tylmann et al., 2012).

error estimation. Finally, the calculation of fluxes (i.e. the amount of annual sediment accumulation per area) will be discussed.

5.1. Varve determination

Prior to varve counting and analysis it is essential to develop a conceptual and idealised model about the processes that form the seasonal succession of laminae for every individual site (Fig. 12). A model of varve formation or varve depositional processes (Lamoureux, 2001) mirrors limnological as well as environmental

conditions in the catchment which control the type of varves. It also characterises the seasonal components used to determine the boundaries between consecutive laminae. Moreover, it helps to identify layers or laminae within a varved record that have limited or no chronological meaning, e.g. turbidites and intermittently bioturbated intervals.

There are five different approaches toward demonstrating the annual nature of laminations and to develop a process-related varve model. These are (i) detailed varve lithostratigraphical studies (e.g. Renberg, 1976; Brauer, 2004; Maier et al., 2013), (ii)

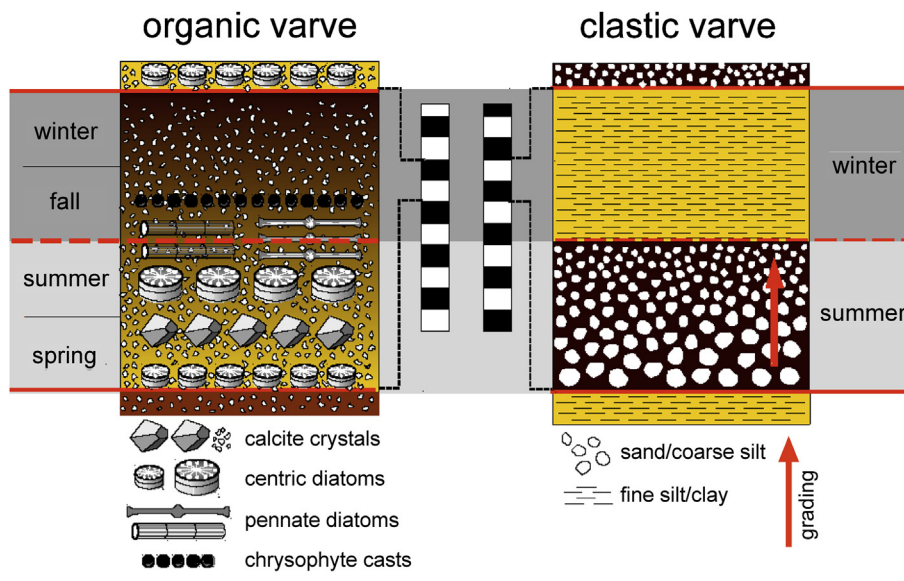


Fig. 12. Simplified models for depositions of a calcareous organic (mixed) varve and a clastic varve (modified from Sturm and Lotter, 1995). In addition to this varve model, there is occasional evidence for missing trends in grain size through the summer layer with coarser particles being deposited in late summer.

sediment-trap studies in the water column in comparison with coevally accumulating laminae on the lake floor (e.g. Kelts and Hsü, 1978; Ojala et al., 2013), (iii) biostratigraphical studies (e.g. Simola, 1977; Card, 1997), (iv) repeated sampling over consecutive years and documenting each new annual increment (e.g. Gälman et al., 2009a; Maier et al., 2013) and (v) documenting the lateral consistency of annual laminations from several parallel sediment cores of the same lake basin (Rydberg and Martinez-Cortizas, 2014). Understanding the internal seasonal succession of annual laminations requires scrutiny of the varve composition by micro-stratigraphical means using thin sections and scanning electron microscopy (SEM) or micro-X-ray fluorescence (μ -XRF) techniques (e.g. Brauer et al., 2008; Martin-Puertas et al., 2012). Sediment traps (Leemann and Niessen, 1994) are typically employed in combination with meteorological and hydrological monitoring of the catchment area to investigate seasonal fluxes, e.g. the sedimentation rate of allochthonous components (Hardy et al., 1996; Lamoureux, 1999; Cockburn and Lamoureux, 2008), sometimes assisted by monitoring stable-isotope ratios (Bluszcz et al., 2009). Micro-palaeontological approaches may focus on the succession of pollen types (Welten, 1944; Card, 1997), diatom species during the course of a year (Simola, 1977; Hausmann et al., 2002) or both (Lotter, 1989). In studying the influences of iron (Fe) and sulphur (S) on the visual appearance of varves and on diagenetic changes of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values, Gälman et al. (2009a,b) succeeded in reliable visual cross-correlation of varve patterns among several cores taken between AD 1979 and 2007 in Lake Nylandssjön (Sweden), thus proving the annual nature of laminae couplets.

5.2. Recovering a laminated sediment record

A complete and continuous sediment record from a study site needs to be recovered for detailed analyses in the laboratory to exploit the full potential of annually laminated sediments. For anchoring the top of the varved sediment record with the year of coring it is mandatory to recover the undisturbed topmost varve at the sediment/water interface. This can be accomplished with the help of freeze-coring devices (Kulbe and Niederreiter, 2003; Renberg and Hansson, 2010) or with box corers that gently extract large blocks of unconsolidated, water-rich sediment (Schimmelmann et al., 1990). Slightly consolidated clastic sediments can be retrieved with a gravity corer (Kelts et al., 1986) or specially designed piston corers (Renberg and Hansson, 2011). For deeper and more consolidated parts of the sedimentary record, different types of piston-coring systems, vibracoring and heavy-weight Kullenberg corers have been employed (Lotter et al., 1997; Mingram et al., 2007). Most piston coring devices recover a long sediment record in the form of one (8–12 m long) or several (1–5 m long) sediment sections that typically lose and disturb a minor amount of sediment at their tops and bottoms. For example, cutting of the up to 12 m long Kullenberg cores into manageable sections of usually 1 m generates minor gaps between sections on a mm-to-cm-scale. Such short gaps can be bridged by taking a second, parallel core at a nearby location with a suitable offset from the first core. This strategy results in a composite profile via cross-correlation of the two parallel cores using high-resolution and continuous core-logging data, e.g. photographs, multi-sensor core-logger (MSCL) and XRF-scanning profiles (Marshall et al., 2012; Martin-Puertas et al., 2012).

It has been argued whether a single varved sediment core or a single composite profile from two neighbouring cores is sufficient to reliably develop a varve chronology and produce time-series of sedimentary palaeoenvironmental proxies. Petterson et al. (1993) maintained that a single varved record from a lake is insufficient for several reasons. Any single core may contain imperfections or

include coring artefacts (especially during the recovery of individual sections of piston coring) that render the core non-representative for a lake's varved sequence in terms of sedimentary macro- and micro-scale lithostratigraphy. Matching results from two or more cores increases the confidence, especially if the cores were taken at different locations in the lake. If in doubt about features in a first sediment core, a second core may confirm the presence of problems like turbidites or erosional layers that were suspected in the original core or the parallel core may confirm that indistinct sections in the first core can be bridged and that consulting a second record allows reliable varve counting. Three-dimensional X-ray computed tomography (CT) scans or micro CT-scans (μ CT) of cores can also help in detecting erosional and other problematic features as they provide a 3D view of the entire core volume instead of the common 2D view of the core surface (Bendle et al., 2015). Parallel cores are also needed for replicate varve counts to enhance the reliability of the varve chronology and to constrain the estimated varve counting error. Finally, the availability of multiple sediment cores ensures a generous supply of sample material for multi-proxy analyses.

5.3. Techniques of investigation

The construction of a varve chronology mandates an unambiguous recognition of the annual cycle in the sediment record. Visual recognition of colour, grey scale or textural differences among seasonal laminae is sometimes possible in thick varves, but typically it is necessary to rely on microscopic or other technical support (Lamoureux, 2001). The most direct method is macroscopic investigation of varves in an outcrop (cf. [historic varve sampling video from 1930](#)) or on the cleaned surface of freshly split sediment core faces. In many cases magnification is needed for analysis.

5.3.1. Analysis of split core faces

Relatively thick (>1 mm) and easily distinguishable varves, e.g. pronounced pairs of pale and dark laminae, can be investigated macroscopically (cf. [Figs. 5, 7A and 10](#)) on the surface of an outcrop or a split sediment core aided by a magnifying glass or a stereo-microscope. However, the necessary precision required at varve thicknesses of less than 1 mm is best achieved using microscale techniques. Varve counting is often facilitated by marking every tenth annual cycle and/or characteristic and unusual varves, e.g. with coloured pins. Depending on the type of sediment, varve counts in anoxic sediment may have to be carried out immediately after core splitting and before the freshly exposed sediment surface becomes oxidised and the optical contrast among laminae is diminished. In contrast, the oxidation of iron-rich, anoxic sediments may also enhance the macroscopic visibility of laminae.

5.3.2. Analysis of thin sections

Finely laminated unconsolidated sediments are generally difficult to analyse because the delicate structures of soft, water-rich deposits are easily disturbed. Wet sediment slabs are subsampled as blocks measuring up to 10 cm in length. The 'osmotic knife' effect is an option to reduce the force needed for cutting into the sediment and to mitigate disturbance (Francus and Asikainen, 2001). Subsequent pore water removal is necessary because impregnation media (usually epoxy resins) are immiscible with water. Freeze drying (Merkt, 1971) yields dry, unconsolidated samples that can accept resin or wax to prepare a hardened block of sediment. Instead of freeze-drying, the use of water-miscible organic solvents such as acetone has the advantage to leave the sediment in a wet condition throughout the entire process minimising textural damages like cracks due to shrinkage. Finally, a multi-component low-viscosity epoxy-resin mixture replaces the acetone and

impregnates the sample (Lamoureux, 1994; Pike and Kemp, 1996). After hardening at an elevated temperature, sediment slabs are cut and polished like rock samples and used to prepare thin (24–30 μm) or thick (>30 μm) sections.

Petrographic microscopy uses normal light (Figs. 3A, 4 and 6A, 13B, C) and polarised light (Figs. 3B, 6B and 7B) with magnifications from 40 $\times$ to 1,000 $\times$ for imaging of the fabric and composition of laminations (Merkt, 1971; Brauer, 2004) and to distinguish between annual laminations and non-annual event-related laminae like turbidites, slumps or volcanic ash layers. Microscopic visualisation of individual autochthonous and allochthonous minerogenic components and the seasonal succession of algal remains can document the annual character of laminations. This approach, called micro-facies analysis, provides more detailed information on seasonal signals than simple inspection of split core faces (Brauer et al., 2009), especially when sedimentation rates were low and in the absence of a clear differentiation between laminae.

5.3.3. Scanning electron microscopy

Scanning electron microscopy (SEM) of varved deposits can provide compositional information with three orders of magnitude higher resolution than light microscopy (Fig. 14; Dean et al., 2001; Ojala and Francus, 2002). The two different modes of SEM are termed secondary electron imaging (SEI) and backscattered electron imaging (BSEI). SEI produces topographic images of dried sediment parallel or perpendicular to bedding planes and of certain sediment components (Figs. 13D and 14). It can document the compositional variation within one lamina or the succession of sedimentary components over the course of one or a few years (Fig. 14) and is able to determine key varve-components such as dinoflagellate cysts (Fig. 13D).

In BSEI the low atomic weight of the epoxy resin impregnating the sediment porosity clearly contrasts from clastic and endogenic grains. Such images can provide quantified porosity data (i.e. density variations) from polished thin sections or sediment slabs, and can also be used to measure grain-size variations and bedding structures (e.g. Francus, 1998; Lapointe et al., 2012). SEM

investigations can be enhanced with an energy dispersive spectrum (EDS) analyser to provide qualitative and quantitative information about the elemental composition of laminae (Dean et al., 1999).

5.3.4. Digital image analysis

Enlarged photographs of split core faces are useful to document sedimentary structures and may even allow varve counting if optical differences between laminae are clearly discernible. Modern photographic techniques take advantage of digital cameras (Pettersen et al., 1999), digital image scanners (Nederbragt and Thurow, 2001; Zolitschka et al., 2001) and line-scan cameras (Francus, 2004; Croudace et al., 2006). Digital images of parallel and overlapping cores from the same site support the initial core correlation. Correlation based on digital images is facilitated by a sufficient amount of marker layers that can be readily distinguished in parallel cores. However, most correlations need to be supported by additional information in the form of physical properties and elemental data. In addition to direct images from the sediment surface, polished blocks of impregnated sediment as well as sediment slabs can be utilised to capture images with a line-scan camera or with a flat-bed scanner. Thin-sections can be digitised by flatbed scanning with transparent capabilities (Fig. 13A). Sandwiching thin sections between two polarizing filters oriented at a 90° angle from each other (De Keyser, 1999), offers additional information about their compositional variations (Fig. 7B).

Digital images can be used to reproducibly determine absolute colour values in comparison with a colour standard (e.g. in the red-green-blue RGB-system, or the CIE L*a*b*-system). Standard colour software can contribute additional stratigraphic information and be combined with semi-automatic image-analysis techniques (e.g. Weber et al., 2010).

Visually indistinct or macroscopically invisible laminations, bioturbation, stratigraphic unconformities, erosional features and slumps sometimes become apparent in X-radiographs that have been obtained formerly with X-ray sources and conventional X-radiography negatives on entire cores, split core halves or resin-

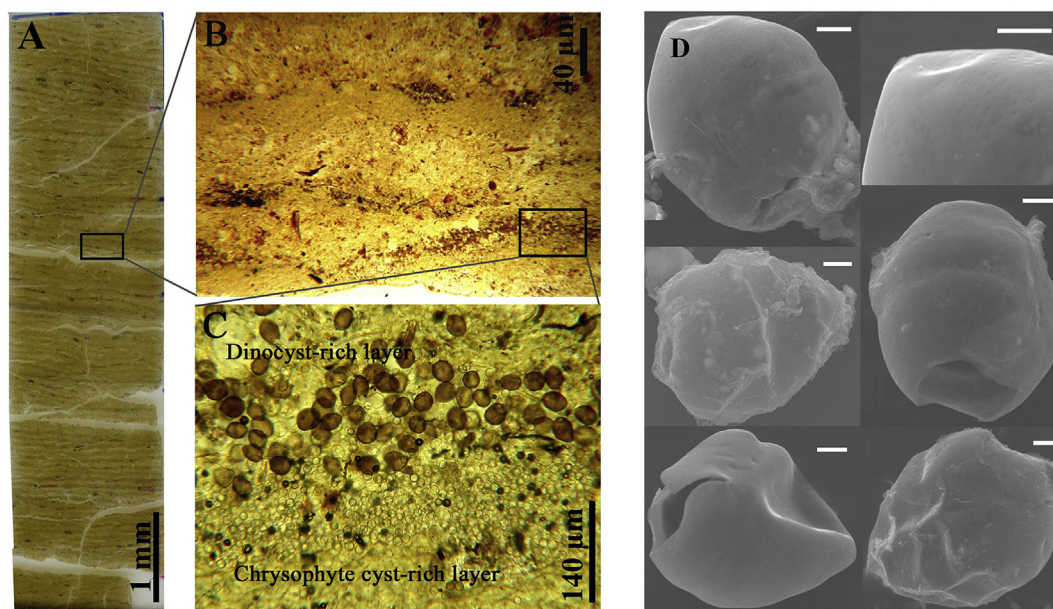


Fig. 13. Varves rich in dinoflagellate cysts from Lake Xiaolongwan in north-eastern China (Chu et al., 2008). (A) Flat-bed scan of thin section in plane light where dark brown laminae are composed mainly of dinoflagellate cysts. Grey laminae consist of siliceous (diatoms, chrysophyte cysts), organic (plant detritus), and minerogenic matter. (B) Microscopic detail of laminations in transmitted light. (C) Dinoflagellate cysts with highest microscopic magnification in transmitted light. (D) Scanning electron microscopic image (SEI) of dinoflagellate cysts showing different types of surface structures (scale bars: 4 μm). Photographs by Guoqiang Chu.

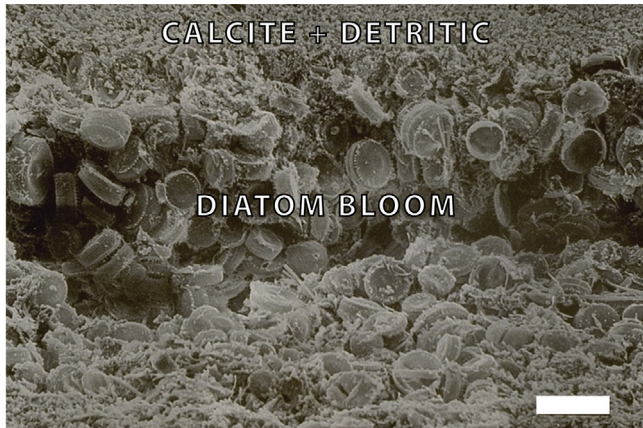


Fig. 14. Annual cycle of a biogenic varve from Soppensee, Switzerland, showing the diatom summer bloom layer and the detritic winter layer. Scanning electron microscope view (SEI) of a fresh sediment cut (scale bar: 40 μm). Photograph by Mike Sturm.

impregnated sediment slabs (Lamoureux, 2001). Modern core scanners are equipped with digital X-ray cameras for continuous recording (Croudace et al., 2006; Marshall et al., 2012). Best results are achieved if X-radiographic imaging is applied to fresh or impregnated sediment slabs with a constant thickness of 1 cm or less to minimise the loss of resolution due to tilted layers. A constant slab thickness and even exposure enhance the quality of X-radiographs (Ojala and Francus, 2002). Digital image processing of X-radiographs yields grey-scale or X-ray density records (Fig. 15) for stratigraphic information (Tiljander et al., 2002; Marshall et al., 2012). CT-scanners can further improve the researcher's capability to identify sedimentary features mainly in clastic varves by preventing the obstruction issue encountered with regular 2D X-radiography, although access to such facilities may be difficult (Fortin et al., 2013; Bendle et al., 2015).

5.3.5. Analysis of μ -XRF scanning data

Micro-X-ray fluorescence (μ -XRF) elemental scanning can provide quantitative elemental profiles and maps across individual varves with up to 20 μm spatial resolution and ideally across the entire length of a record (Shanahan et al., 2008; Marshall et al., 2012). Depending on seasonal fluxes and mean sedimentation

rates, the settings of a scanner need to be optimised to (i) detect all elements relevant for the distinction of the annual sedimentation cycle, and (ii) perform at least ten measurements across each varve to provide sufficient and representative data for every seasonal layer (Marshall et al., 2012). Minimizing the acquisition time to limit desiccation and reduce analytical cost as well as to account for reliable processing of non-horizontal layers should be considered depending on the technical capability of the instrument. A successful setup can identify and geochemically characterise sub-mm scale annual laminations as demonstrated by Fig. 16.

5.4. Varve counting

5.4.1. Counting tools

Counting of laminae for developing a varve chronology requires prior determination of the annual structure of laminations as visualised for two varve types in Fig. 12. A varve chronology is established through replicate varve counts and thickness measurements along at least three transects (Lamoureux, 2001) using either microstratigraphic analyses of thin sections (Brauer, 2004), digital image analysis (Francus, 2004), or μ -XRF-based techniques (Marshall et al., 2012). All three methods have specific advantages and disadvantages. Microstratigraphic investigation allows scrutiny of the internal structure and composition (microfacies) of individual varves and is thus able to identify layers of no chronological significance (e.g. turbidites). At least two researchers should carry out the measurements independently because results rely on sedimentological experience and subjective decisions (Fig. 17).

Digital images can be shared among workers and result in more objective and faster counting of varves. Furthermore, digital files can be easily archived and retrieved for re-counting of varves to improve chronologies. New software offers statistical tools (e.g. Nakagawa et al., 2012) for enhanced manual control during layer identification. Future automated methods could potentially reduce the subjective error estimates of manual counts by generating varve chronologies with more objective and quantified uncertainties (Weber et al., 2010). A comparison of manual and (semi)automatic varve counting methods by Kinder et al. (2013) used two computer programs, the Cybis Coordinate Recorder (CooRecorder; <http://www.cybis.se/cbeewing/index.htm>) and the BMPix and PEAK tools (Weber et al., 2010). CooRecorder processes images of the varved record, requires manual and subjective determinations of varve boundaries, registers coordinates of boundaries, and

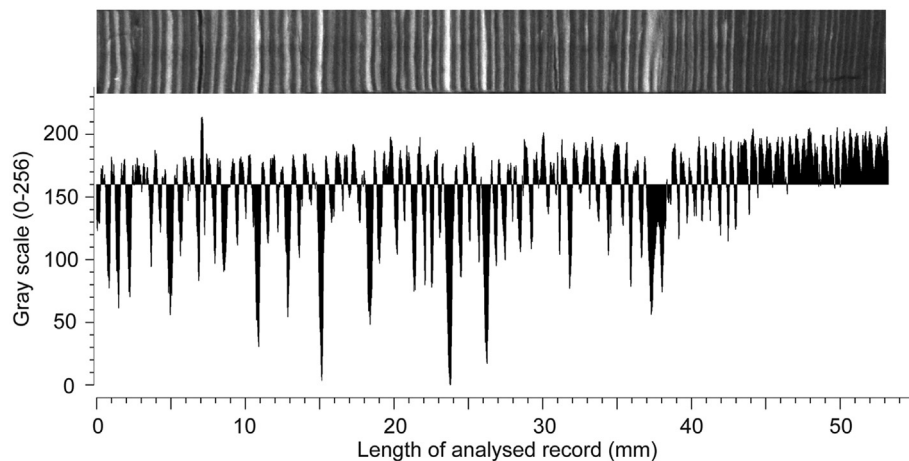


Fig. 15. (Top) X-radiographic density image of Lake Nautajärvi clastic-biogenic varves for the time interval 205 to 306 varve years BC. (Bottom) Measured grey scale values from line-scan analysis. Ojala and Tiljander (2003) used this semi-automated image analysis method to examine and digitally record the nearly 10,000-year-long varve sequences from Finnish lakes Nautajärvi and Korttajärvi (modified after Tiljander et al., 2002).

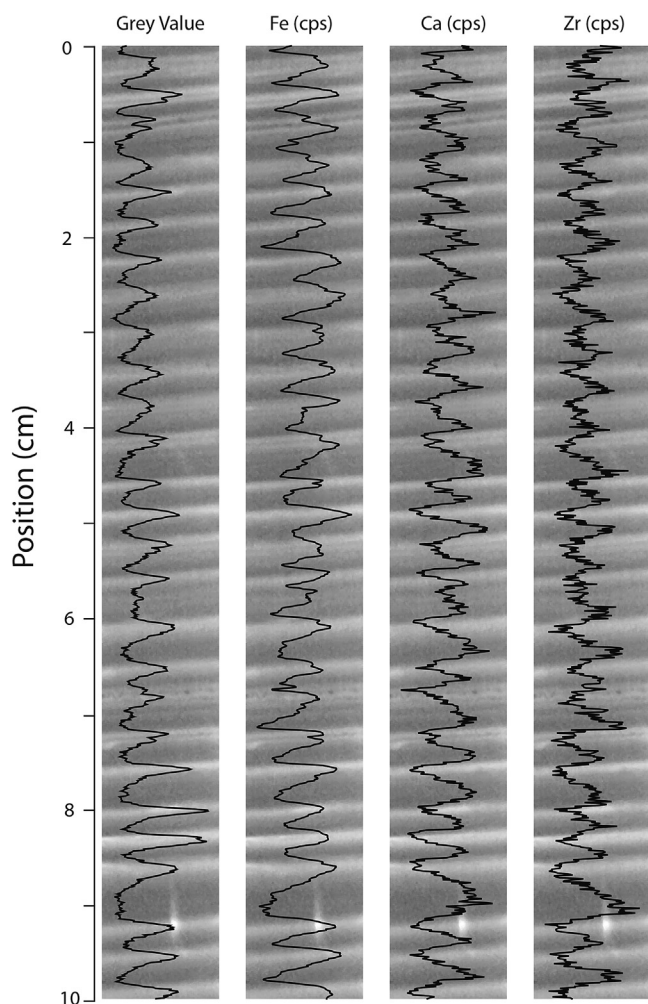


Fig. 16. μ -XRF analysis across clastic-biogenic varves from Grand Lake, Labrador, Canada. Radiographic images are overlain by grey scale profiles, iron (Fe), calcium (Ca), and zirconium (Zr) abundances. Low grey scale values (dark) point to dense sediments. Elemental values are expressed in counts per second (cps). Coarse-grained sediments are rich in Zr and Ca, while clays and organic matter are characterised by high Fe content. Thus, at Grand Lake varves are characterised by dark and runoff-related spring sublaminae which are rich in allochthonous elements such as Ca and Zr while the pale summer to fall sublaminae are enriched in Fe. Image courtesy of David Fortin.

calculates varve thickness data. A major advantage compared to manual counts is that disputed varve boundaries can be easily reviewed and revised by other analysts. On first sight, the BMPix tool works more objectively as it extracts grey-scale data from bitmap images, followed by the PEAK tool for semi-automatic counting and measuring of laminations (Weber et al., 2010). Proper varve identification and counting with the PEAK tool require specific settings to adjust the algorithms for different varve types, thicknesses and colours. Running this semi-automatic program with constant settings throughout an entire sediment profile can produce unrealistic results (Kinder et al., 2013), because the analysed varve parameters may change over depth and require adjustments in settings that add another type of subjective decision.

Both types of software offer integrated estimates of uncertainty as a significant advance compared to manual varve counting. However, very thin varves as well as very thick varves with complex and highly variable structures enhance the probability of erroneous counts because mere images used by these counting tools offer little information on the chemical and/or biological composition of laminae (Kinder et al., 2013). Such information is necessary to discriminate non-annual and annual from seasonal signals.

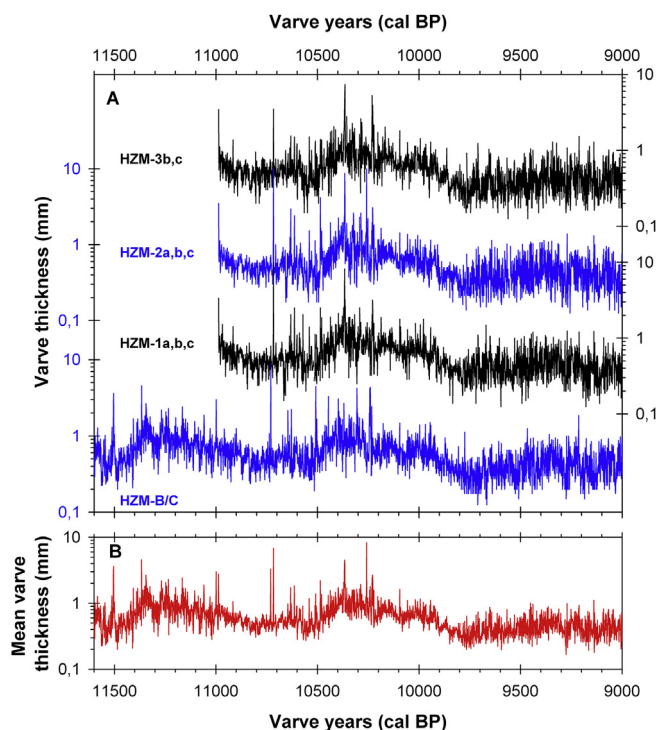


Fig. 17. (A) Varve counts and thickness variations (logarithmic scale) determined independently by three different scientists on ten profiles compiled to form four continuous sequences (HZM-1a,b,c, HZM-2a,b,c, HZM-3b,c and HZM-B/C) from Lake Holzmaar in Germany for the early Holocene (11,600–9000 cal BP). (B) Data compiled into one unified record of mean varve thickness display less noise and should be preferred for reconstruction (modified after Zolitschka, 2007).

Recent developments with μ -XRF have provided a new approach for varve counting that can be complementary to microstratigraphic varve counts via PeakCounter (Marshall et al., 2012) and allows the superposition of digital images of varved sequences (images and X-radiographs) and chemical profiles provided by μ -XRF. The user determines varve boundaries based on several parameters and assigns a score for each varve identification based on the number of matched criteria. This score can be used as a measure of counting uncertainty.

5.4.2. Constructing age models for varve sequences

Based on the cumulative thickness of all laminae that jointly comprise each annual varve (cf. Fig. 17B), an age–depth model (i.e. varve chronology) is established with as many data points as varves have been counted (Figs. 18 and 19) to attribute ages to all depth intervals of the record. Varve chronologies with secure and absolute anchoring are based on incremental dating and assign dates in varve years ($\sim$ calendar years), if the chronologies are continuous and extend to the sediment surface (i.e. the present day or the year of coring) or to some other absolutely dated sediment marker like a historically documented flood or tephra deposit. For all chronological aspects it is necessary to provide the reference year of the record.

Occasional inconsistencies are either related to incomplete records (Andr n et al., 1999) or to ambiguous laminations and hiatuses that reduce the reliability of the obtained chronology, especially for long varve records with varying characters of annual cycles responding to highly variable environmental conditions (e.g. at the glacial-to-interglacial transition; Zolitschka and Negendank, 1996; Zolitschka et al., 2000; Marshall et al., 2012; Scholaut et al., 2012). Such changes in the depositional environment may interrupt varve formation or result in partially indistinct records. Interpolation of the

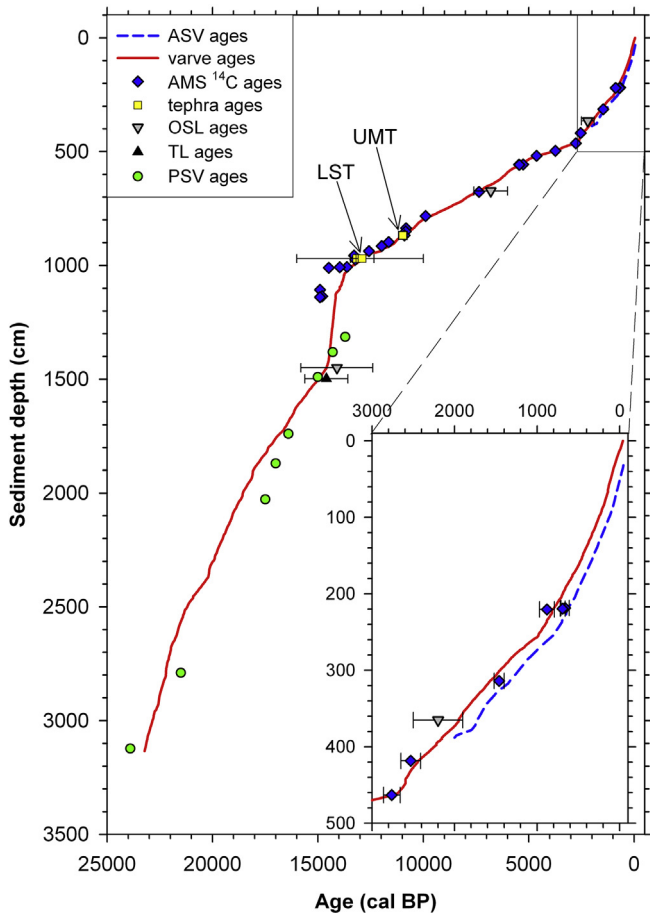


Fig. 18. Age–depth model of Lake Holzmaar in Germany based on varve counts (red line) obtained by microstratigraphic analysis of thin sections. Also plotted are calibrated ^{14}C ages of terrestrial plant macrofossils, calibrated AMS ^{14}C ages of Ulmener Maar Tephra (UMT) and Laacher See Tephra (LST), $^{238}\text{U}/^{230}\text{Th}$ and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of LST (tephra ages), as well as optically stimulated luminescence (OSL) ages, one thermoluminescence (TL) age, and dates based on correlation of inclination features of palaeomagnetic secular variation (PSV) records between Lake Holzmaar and Lac du Bouchet, France. The inserted graph shows an enlargement of the youngest 3000 years with details of the parallel-shifted (log-in time) archaeomagnetic secular variation (ASV) age–depth relationship (dashed line; modified from Zolitschka et al., 2000).

age–depth model across intervals featuring homogenous sediment or indistinct annual laminations is the best option to overcome this common problem of incompletely varved records. In practice, this is typically achieved by applying sedimentation rate estimates from neighbouring and well-varved sections. This rather subjective way of interpolation introduces uncertainty by assuming overall constant sedimentation rates across varved and non-laminated sections reflecting times of drastic environmental changes. A novel automated approach for interpolation of ‘varve counts’ by Scholaut et al. (2012) uses a program that analyses the seasonal layer distribution and automatically produces an estimate for sedimentation rates while avoiding operator subjectivity. An application of this method to the Lateglacial varved sections of Lake Suigetsu (Japan) yielded an overall varve-based chronology that compared favourably with the high-resolution radiocarbon chronology within the 1σ range of calibrated ^{14}C ages (Scholaut et al., 2012).

5.4.3. Error estimation

The chronologies of all consecutive counts of varves are highly accurate for most recently added increments but are suffering from increasing uncertainty due to cumulative errors with increasing depth or age (Ojala et al., 2012). Nevertheless, the precision and

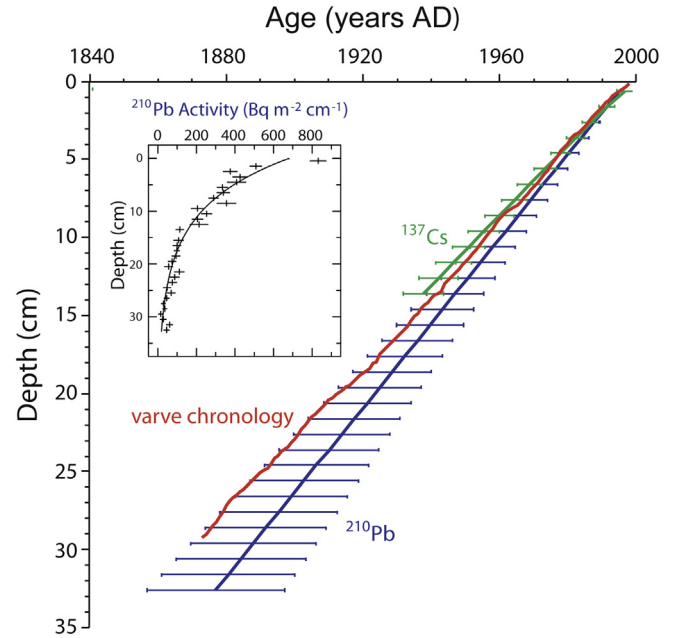


Fig. 19. The varve chronology (red line) of Sacrower See in Germany agrees well with ^{137}Cs (green line) and ^{210}Pb (blue line) radiometric ages (based on the constant initial concentration model, CIC) within the error bars of 95% confidence intervals. Insert displays ^{210}Pb activity vs. depth (modified after Lüder et al., 2006).

accuracy of varve-count chronologies are typically far superior to chronologies based on radiometric methods and can pinpoint ages within a few years.

Systematic errors of varve chronologies are attributed to several sources (Sprowl, 1993):

- Technical problems: incomplete core recovery, sediment gaps between core segments, coring artefacts, missing or disturbed topmost sediment, lacking core overlap, and uncertain correlation of parallel core segments.
- Depositional events: erosion of topmost varves at the onset of high-energy depositional events (turbidites, slumps, volcanic ash layers). Disturbance of varves throughout a lake may occur via deposition of dropstones and large plant or animal remains (e.g. tree trunks or animal carcasses) or earthquakes.
- Sedimentation rates: Very high (>20 mm) or low (<0.2 mm) varve thicknesses complicate the distinction among individual varves. Thick varves are sometimes composed of more than 10 seasonal laminae that are related to individual events like rainfall, runoff or algal blooms. Moreover, thick individual seasonal and event laminae are sometimes difficult to distinguish from the annual cycle. Thin varves, on the other hand, feature a compressed annual cycle that is difficult to discern or even partially missing. Unusually thin varves can be mistaken as a single lamina of a seemingly thicker varve.
- Varve preservation: changes in lake level or autochthonous productivity (eutrophication, oligotrophication) influence the oxygenation of bottom water and thus the preservation of lamination (cf. Figs. 10 and 11).

Errors can be negative (missing or unrecognised varves) or positive (erroneous and superfluous varves counted by the analyst; cf. Lamoureux and Bradley, 1996). Technical problems and event deposits can be avoided or minimised by using appropriate coring techniques and suitable coring sites. The recovery and cross-correlation of multiple parallel and overlapping cores tend to minimise errors (cf. Fig. 17). The other sources of systematic errors

related to sedimentation rate and varve preservation must often be regarded as an inherent problem to varve chronologies that emphasises the importance of varve count verification via cross-checking of varve chronologies against other independent dating methods. Varve counting errors cannot be avoided completely when counting thousands of varves along extended sedimentary records (e.g. Ojala et al., 2012).

The varve counting error can be determined as the root of the mean squared error of multiple counts along defined transects, ideally on multiple cross-dated cores from the same site (Lamoureux, 2001). Preferred practises include maximum and minimum deviations from the mean (Lotter and Lemcke, 1999), tie-points as marker horizons throughout the record, and replicate counts between marker horizons allowing individual error estimates for each section (Fig. 20) and for the entire record (Lamoureux, 2001; Ojala and Tiljander, 2003).

Replicate varve counts across well developed and undisturbed varve sequences show little variation between alternate counts by different observers and a low overall error, for example $\pm 1\%$ for a mean varve thickness of 0.67 mm a^{-1} at Lake Nautajärvi, Finland (Fig. 20). In contrast, the disturbed varved sediments with less distinct varve boundaries at Steel Lake, USA express a counting error of $\pm 8.4\%$ in spite of a higher mean varve thickness of 1.22 mm a^{-1} (Tian et al., 2005). The compilation by Ojala et al. (2012) of estimated varve counting errors from 108 published varve records reports that only 62 records (57%) provide error estimates from zero to $\pm 15.0\%$ with a mean of $\pm 3.1\%$ (standard deviation 2.9%). However, the overall mean is biased by a few records with very large errors. An error of $\pm 2.0\%$ is more realistic for most varve chronologies (Ojala et al., 2012) and matches the earlier estimate by Renberg (1983).

In general, counting error estimates should be reported together with age estimates. It should be stated which uncertainty contributions are included in the presented uncertainties and whether reported uncertainties are Gaussian-style uncertainties (1σ or 2σ standard deviation) or stochastic (Brauer et al., 2014).

5.5. Verification

The determination of varve counting errors as variance between values of different investigators or replicate counts only gives a measure for the precision of varve counts. It does not provide any indication of the chronological error (accuracy) of the entire record as a result of undetected systematic errors that can only be determined via multiple independent dating approaches (multiple dating: Figs. 18 and 19).

Varve chronologies are potentially hampered by internal inconsistencies or hiatuses and thus require independent verification even if varves are distinct and easily distinguished. All underlying varve-formation models (e.g. Fig. 12) rely on assumptions about the nature of the annual varve signal that need to be tested with process studies or by applying independent dating techniques (cf. Figs. 18 and 19). The most common verification relies on radiometric techniques like AMS ^{14}C for records reaching back as far as ca 50,000 years (Bronk Ramsey et al., 2012). Sometimes an uncertain connection of varved sediment records to the present-day can be clarified with relatively short-lived ^{137}Cs and ^{210}Pb radioisotopes (Fig. 19), but there are many varve chronologies that cannot be unambiguously tied to the present-day or any other absolute time marker. Such varve chronologies that are annually spaced without anchor are called 'floating' (e.g. Kienel et al., 2005). A floating chronology may hope to find future anchoring via successful cross-correlation with an absolute chronology.

Additional chronostratigraphic methods like tephrochronology (V.C. Smith et al., 2013; Wulf et al., 2013), palaeomagnetic techniques based on palaeomagnetic secular variations (PSV; Stockhausen, 1998; Ojala and Tiljander, 2003; Snowball et al., 2007; Cook et al., 2008; Stanton et al., 2010) and relative palaeointensity (RPI) of Earth's magnetic field (i.e. magnetostratigraphy; Heltia-Hovi et al., 2011) or marker horizons that link sediment records to historical data or events (Kienel et al., 2005) can be used for absolute or approximate anchoring of varve chronologies, depending on the accuracy of the chronostratigraphic information.

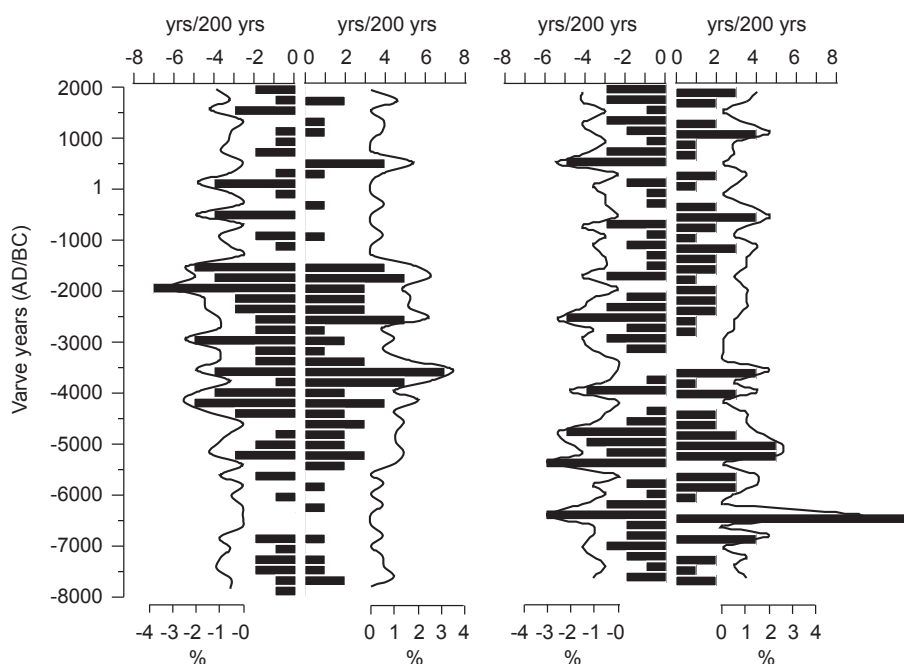


Fig. 20. Varve counting error estimates for clastic-biogenic varved Finnish lakes Nautajärvi (left) and Korttajärvi (right). Varve chronologies are based on X-radiographic densitometry, semi-automated varve counts, and stereomicroscopic examination of fresh sediment and polished surfaces of resin-impregnated sediment blocks spanning the last 10,000 years. Counting errors are estimated to $\pm 1\%$ for both lakes and presented at 200-year intervals as possible extra or missing varves (bar scales) and as positive/negative percentage deviations (black lines) (modified from Ojala and Tiljander, 2003).

Biostratigraphic methods (e.g. palynology) can provide precise chronological tie-points in particular settings, such as the appearance of new pollen taxa related to European settlement in North America (e.g. Besonen et al., 2008). More often, these techniques are used to transfer the time control from varved to non-varved records (Snowball et al., 2007), to match records, e.g. with isochronous tephra layers (Zillén et al., 2002) or to facilitate a regional correlation (Litt et al., 2009).

5.6. Calculation of flux rates

Geochemical data of varved records are typically documented as weight-percentage values, which change over time as fresh sediment becomes compacted and loses pore water. For the same reason varve thickness expressed in millimetres or as sedimentation rate (SR) in mm a^{-1} decreases with depth. This bias can be avoided via calculations of sediment (mass) accumulation rates (SAR) for palaeoclimatic and environmental reconstruction. Varved sediment sequences theoretically allow for the estimation of SAR values with annual resolution, but calculations are limited by necessary dry bulk density (DBD) measurements that are often carried out at a lower spatial resolution (at best 1 cm) whereas varve thickness may range from 0.07 to 27.3 mm with a mean of 1.84 mm (Ojala et al., 2012). SAR is calculated by multiplication of DBD with SR of the same profile (Equation (4)):

$$\text{SAR}(\text{g cm}^{-2} \text{ a}^{-1}) = \text{DBD}(\text{g cm}^{-3}) \times \text{SR}(\text{cm a}^{-1}) \quad (4)$$

The resulting data are called ‘flux rates’ if SAR is related to certain sediment components. For example, a transformation of organic matter content (org) into flux rates of organic matter (SAR_{org}) is accomplished by multiplication of org with the corresponding SAR value (equation (5)):

$$\begin{aligned} \text{SAR}_{\text{org}}(\text{g cm}^{-2} \text{ a}^{-1}) &= \text{org}(\text{weight \%}) / (100 \times \text{SAR}) \\ &\times (\text{g cm}^{-2} \text{ a}^{-1}) \end{aligned} \quad (5)$$

Although first flux-rate calculations in annually laminated sediments date back almost 70 years (Welten, 1944), the concept has been rarely applied (Zolitschka, 1998; Ojala and Alenius, 2005; Cook et al., 2008) and awaits wider acceptance with the advent of automated and non-destructive logging instruments for economical measurement of sediment properties (Fortin et al., 2013). These new techniques can generate continuous and high-resolution physical and chemical sedimentary parameters across varves with a resolution down to 100 μm and offer opportunities to calculate SAR time series with annual resolution.

An example of how varve thickness can influence analytical results is provided by Fig. 21. The four sections represent ca 1 cm each. If sampled with 1 cm resolution, one sample from AD 1810 (Fig. 21A) would include only 2 years of deposition while a sample from 6400 BC (Fig. 21D) would include 27 years. Assuming a comparable annual flux of chemical elements or biological remains (e.g. pollen grains) for both examples, weight-percentage values would indicate a 13-fold increase for 6400 BC. This bias can be avoided by calculation of flux rates.

6. Advances in the utilisation of varved sedimentary records

In the first varve review (O’Sullivan, 1983) the most important applications of annually laminated sediment sequences were pollen-related studies. However, over the past 30 years these sediments have been used at an ever-increasing rate, with

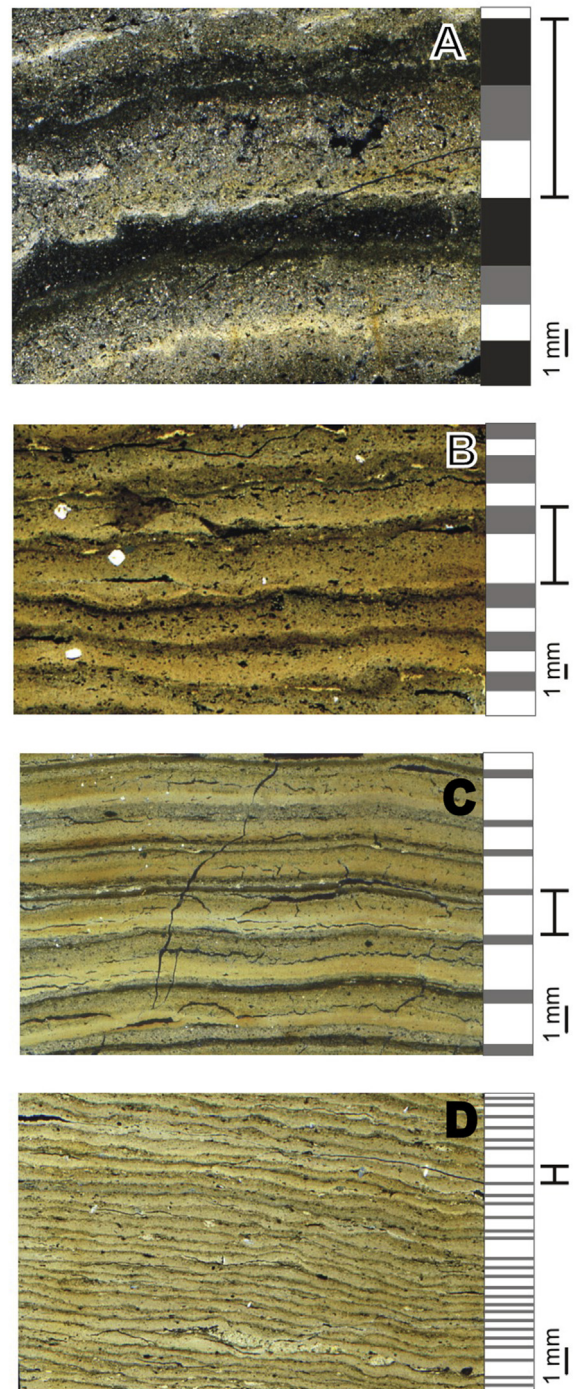


Fig. 21. Varve structures of four different depth intervals in Lake Szurpity, Poland. All depth intervals document a similar varve composition: thicker and pale laminae are composed of calcite, whereas thinner and dark laminae are composed of organic matter and minerogenic detritus (varve couplets are indicated to the right by grey and white bars). The trend of increasing varve thickness over time results from changes in sediment accumulation rates during the Holocene, primarily due to eutrophication, and a minor extend is related to compaction. Images are based on flat-bed scans of resin-impregnated sediment slabs. Central depths and ages of images A–D are: (A) 27 cm and AD 1810 $\pm$ 30; (B) 125 cm and AD 1430 $\pm$ 38; (C) 360 cm and 330 BC $\pm$ 50; (D) 740 cm and 6400 BC $\pm$ 101 (modified from Kinder et al., 2013).

continuously higher resolution and for a much wider range of climatic and environmental reconstructions. This is documented by a search for the term “varve*” in the Web of Science (Thompson Reuters) carried out on March 9, 2015: 89 varve-related papers

were published until the year 1982 and provided the base for O'Sullivan's review. Since 1983 an additional number of 1301 publications were released.

The growing awareness of climatic and environmental changes in the late 20th century sparked tremendous interest in high-resolution and well-dated environmental and climatic information from varved archives. The development of varve science was additionally fuelled by technological advances. Improved piston and freeze-corers, ^{14}C -AMS for dating of small samples, computerised auto-samplers for fast geochemical analyses, and the generally increased computational power of statistical packages all allowed novel and in-depth varve analyses. Most recent advances enabled to perform detailed studies on a sub-millimetre spatial scale via advanced microscopic and image analyses of thin sections (Francus, 2004; Hambley and Lamoureux, 2006), non-destructive μ -XRF core-scanning for high-resolution geochemical sediment characterisation (Zolitschka et al., 2001; Croudace et al., 2006) as well as Fourier transform infrared spectroscopy (FTIRS; Rosén et al., 2011) and scanning reflectance spectroscopy in the visible spectrum (Trachsel et al., 2010) for high-resolution analyses of organic and minerogenic sedimentary parameters. Some of these techniques can even retrieve subannual (seasonal) information from varves. In the following chapters, a selection of applications and highlights of technical developments since O'Sullivan's (1983) review are discussed.

6.1. Radiometric dating

Radiometric techniques are commonly used for dating of late Quaternary records (see overviews in Wagner, 1998; Lanphere, 2001; Walker, 2005; Taylor and Bar-Yosef, 2014), especially for lake sediments. Massive lacustrine sediments without annual laminations completely rely on radiometric dating for absolute age control. The isotope ^{137}Cs has been released from nuclear industrial point sources and can provide age information for the last 50 years, while the natural radioisotopes ^{210}Pb and ^{14}C can be used for dating within the last ca 150 and 50,000 years, respectively. The ca 200–300 year dating gap between the two fastest decaying isotopes and ^{14}C has not yet been filled with alternative suitably

decaying radioisotopes, although ^{32}Si might develop as a potential candidate to cover the last 1000 years (Morgenstern et al., 2013).

Radiometric dating is often applied to confirm the annual character of finely laminated sediments (Ojala et al., 2012). However, the biggest advantage of varved sediments, once their annual cycle has been determined, is to provide an independent and continuous time scale in calendar years for discrete radiometrically or otherwise dated samples. Thus an accurately calibrated and validated varve chronology can be transferred to, and compared with radiometric “model ages”. Selected examples for this approach are highlighted within the following four sections.

6.1.1. Varves and ^{137}Cs dating

Cesium-137 (^{137}Cs) has no natural sources. The timing of anthropogenic ^{137}Cs maxima relates to atomic bomb tests (registered globally and centred around AD 1963) and nuclear industrial emissions and accidents (e.g. Chernobyl AD 1986 outfall affecting parts of Europe and Western Asia). ^{137}Cs is mostly adsorbed by clays and organic matter. With a half-life of only 30 years, ^{137}Cs is used as a tracer to quantify sedimentation rates in reservoirs, lakes, wetlands, coastal areas, and flood plains (Ritchie and McHenry, 1990). Discrete stratigraphic ^{137}Cs peaks are used to confirm that lamination couplets are truly annual in nature and that varve records extend continuously to the most recently deposited lamination (e.g. Lima et al., 2005; Lüder et al., 2006; Boës and Fagel, 2008; Kinder et al., 2013; Tylmann et al., 2013a; Amann et al., 2014). The availability of instrumental data from monitoring efforts across the last ca 50 years makes this time slice especially important for sedimentary proxy calibrations. Although the method of ^{137}Cs dating is usually straightforward (cf. Fig. 19), complications arise in regions affected by high fallout of Chernobyl ^{137}Cs . For instance, in Lake Nylandssjön in northern Sweden, the ^{137}Cs record is affected by sediment-specific post-depositional diffusion and by the legacy of ^{137}Cs from 1960s atomic bomb testing (Fig. 22). Detection of these effects was made possible by a sequence of 11 annually laminated sediment freeze-cores recovered between the years 1986 (i.e. three weeks before the Chernobyl accident) and 2007 (Klaminder et al., 2012; Appleby, 2013). The core taken prior to the Chernobyl accident records the nuclear weapons testing of the early 1960s as a valuable time-marker (Fig. 22). However, the weak ^{137}Cs signal for

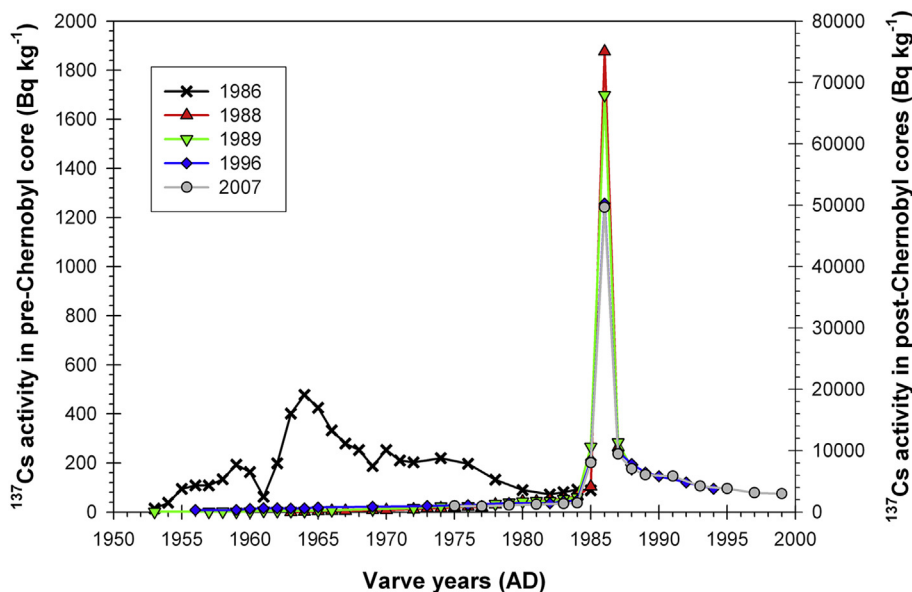


Fig. 22. ^{137}Cs fallout measured in five cores collected from varved Lake Nylandssjön in Sweden during the period AD 1986–2007. The sediment core from 1986 was collected just before the Chernobyl nuclear accident (data from Klaminder et al., 2012; graph modified from Appleby, 2013).

the 1963 nuclear weapon tests in sediment cores taken after the Chernobyl accident has been obliterated by later downward diffusion of high concentrations of Chernobyl-derived ^{137}Cs . The deposition of Chernobyl ^{137}Cs was limited to parts of the northern hemisphere; whereas the southern hemisphere remained unaffected, e.g. the study of Lago Puyehue varves (Chile) by Boës and Fagel (2008) documented a single peak of ^{137}Cs from 1960s bomb testing. Even much of the northern hemisphere did not receive significant ^{137}Cs fallout from Chernobyl. Sun et al. (2006) found no evidence of Chernobyl-derived ^{137}Cs in varved sediment of Lake Bolterskardet on Svalbard. The assumed absence of radiogenic fallout from Chernobyl in North America has been challenged by several authors. Lima et al. (2005) found a ^{137}Cs peak corresponding to AD 1986 within varved sediments of an anoxic estuarine basin along the coast of southern Rhode Island, and increased ^{137}Cs activity due to the Chernobyl accident was also observed across the Canadian High Arctic (e.g. Lamoureux, 1999; Cuven et al., 2011).

6.1.2. Varves and ^{210}Pb dating

The ultimate parent isotope of lead-210 (^{210}Pb) is ^{238}U that has a long half-life of 4.47 Ga and still retains 49% of its primordial concentration (Thompson, 2007). ^{238}U slowly decays via ^{234}Th , ^{234}Pa , ^{234}U , ^{230}Th , and ^{226}Ra to the noble gas radon ^{222}Rn in rocks and sediments from where ^{222}Rn partially outgases and enters the atmosphere at the average rate of ca 42 atoms $\text{min}^{-1} \text{cm}^{-2}$ of land surface. During its short half-life of only 3.8 days ^{222}Rn mixes in the troposphere where it decays via short-lived intermediate nuclides ^{218}Po , ^{214}Pb , ^{214}Bi , ^{214}Po to ^{210}Pb with a half-life of 22.26 years (Dickin, 2005; Schmidt and Cochran, 2010). ^{210}Pb has an atmospheric residence time of about 10 days and deposits with rain, snow, and via diffusion and adsorption. Comprehensive overviews of the ^{210}Pb cycle in the environment are provided by Robbins (1978) and El-Daoushy (1988). It attaches to settling particles where its decaying radioactivity can be used to date less than 150-year-old sediments. If one of the parent isotopes is also present in the sediment and produces autochthonous ^{210}Pb (i.e. supported ^{210}Pb), only the unsupported or airborne (i.e. excess) fraction of ^{210}Pb must be considered for dating.

The result of ^{210}Pb dating strongly depends on the model used for interpretation (Appleby, 2008). In contrast to ^{137}Cs dating where distinct peaks of radioactivity are attributed to well-defined events, ^{210}Pb dating relies on the decay rate of initially deposited ^{210}Pb to construct a time scale. The original ^{210}Pb concentration of a sediment sample at the time of deposition needs to be estimated. The simplest approach assumes a steady state system where the ^{210}Pb concentration of all varves in a laminated sequence had been constant at the time of deposition (i.e. model of constant initial concentration – CIC). A comparison of CIC-based age models for three varved sediment records from Finland established considerable deviations from independent varve chronologies (Appleby et al., 1979). In contrast, the constant rate of supply (CRS; Appleby and Oldfield, 1978) age model takes into account changes in sedimentation rate whereby the initial ^{210}Pb concentrations of individual varves are inversely proportional to the sedimentation rate (SR). As a result, the CRS model's age–depth relationship agrees much closer with the varve-count-based chronology (Appleby et al., 1979). It is generally necessary to validate ^{210}Pb age–depth models with other independent chronostratigraphic methods. Typically this is achieved with ^{137}Cs for the same record. However, for CIC, CRS and also for another model that takes flux rates into account (i.e. constant flux and constant sedimentation, CFCS) the underlying assumptions are not always fully justified and may result in unreliable chronologies (Smith, 2001). Therefore, inductive approaches (e.g. the sediment isotope tomography model, SIT) were introduced for age–depth modelling without

underlying assumptions for initial ^{210}Pb activity, flux and sedimentation rates (Carroll and Lerche, 2003).

The example of Lake Łazduny's varve chronology in Poland demonstrates that the combination of different ^{210}Pb age–depth models (CIC, CRS, CFCS and SIT) with the ^{137}Cs record offers advantages for better understanding the principles of radiometric dating techniques for varves (Tylmann et al., 2013b). The CIC, CRS, and CFCS ^{210}Pb dating-models in this case produced diverging results while the SIT model compared best with varve counts and ^{137}Cs deposition curves. Therefore, systematic testing and validation of ^{210}Pb dating models are required to yield a reliable and robust ^{210}Pb chronology (Tylmann et al., 2013b). Depending on the individual varve record, the application of a select model seems to provide best results, e.g. (i) the CIC model proved to be superior for Frickenhauser See (Enters et al., 2006) and Sacrower See (Fig. 19; Lüder et al., 2006), both in Germany, (ii) the CRS model was selected for Lake Bosumtwi in Ghana (Shanahan et al., 2008), and (iii) the CFCS model was advantageous for Lago Puyehue in Chile (Arnaud et al., 2006; Boës and Fagel, 2008).

A special case was presented for the 8400 year-long varved record of Lake Szurpily in Poland suffering from a disturbed section in the top 20 cm (Kinder et al., 2013). The combination of ^{210}Pb and ^{137}Cs chronologies bracketed this disturbed section to AD 1858–1998 and thus bridged the gap between the uppermost non-laminated interval to varves below 20 cm.

6.1.3. Varves and ^{32}Si dating

Silicon-32 (^{32}Si) is produced by cosmic-ray spallation of argon in the upper atmosphere. Its half-life offers the potential to fill the dating gap between chronologies based on the shorter-lived isotopes ^{137}Cs and ^{210}Pb , and those based on the longer-lived ^{14}C (Fifield and Morgenstern, 2009). After fallout in precipitation, ^{32}Si can be used to constrain the mixing of large bodies of water, glacier dynamics, and siliceous sediment accumulation on a time scale of about 1000 years. The half-life of ^{32}Si had been initially narrowed down from between 101 ± 18 and 330 ± 40 years to an estimation of 178 ± 10 years based on accurately varve-dated sediment from Lake Kassjön in northern Sweden (Nijampurkar et al., 1998). Subsequently, the half-life of ^{32}Si was revised to ca 140 years but still bears an uncertainty of $\pm 10\%$ (Fifield and Morgenstern, 2009). In spite of the difficulty of ^{32}Si -dating requiring an impractically large sample size for all sediment records in general and varve studies in particular, the chronometric potential of ^{32}Si is close to being realised as a result of recent improvements in analytical methods (Fifield and Morgenstern, 2009).

6.1.4. Varves and ^{14}C dating

Radiocarbon dating is based on the 5730-year half-life of the cosmogenic radioisotope ^{14}C (background information on radiocarbon dating is provided by e.g. Wagner, 1998; Walker, 2005; Taylor and Bar-Yosef, 2014). It is produced predominantly via neutron capture of ^{14}N in the atmosphere where ^{14}C is rapidly oxidised to carbon dioxide ($^{14}\text{CO}_2$). Atmospheric mixing leaves only small regional and temporal differences in $^{14}\text{CO}_2$ -abundance. A dynamic equilibrium is reached between dissolved inorganic carbon (DIC) in surface waters and atmospheric $^{14}\text{CO}_2$. Terrestrial and aquatic autotrophic organisms utilise ^{14}C from CO_2 and DIC to biosynthesise organic matter, from where ^{14}C in biomass permeates through the food chain. Once incorporation of ^{14}C -containing fresh biomass has stopped (for example, upon “biological death” of biomass), but also in the cellulose of tree-rings one year after formation the decay of ^{14}C serves as the basis for dating to ages up to 50,000 years.

Uncalibrated or “conventional” ^{14}C -ages BP (BP = before present, i.e. years before AD 1950) assume a constant cosmogenic

production rate of ^{14}C through time. These dates often differ substantially from correct calendar ages because the cosmogenic production rate of ^{14}C has varied through time. Elevated solar activity emits enhanced solar wind that combines with the magnetosphere and shields the Earth from cosmic rays. This causes the production of cosmogenic isotopes to decrease. Modern radiocarbon calibration programs compensate for these variations with the help of calibration curves based on other well-dated natural archives like tree rings, corals and, more recently, varved sediments. Uncalibrated ^{14}C -ages BP are calibrated to yield radiocarbon ages expressed in terms of cal BC, cal AD or cal BP. Alternatively, the terms BCE and CE for (Before) Current Era are in use. The term cal BP refers to calendar years before AD 1950 and can be translated to the historical ages cal BC or cal AD.

The introduction of AMS- ^{14}C dating in the early 1990s greatly reduced the required sample size and made it possible to extend the ^{14}C dating of varved sediment records into the Lateglacial. As annually laminated lake sediments provide a similar temporal resolution as tree-rings and often contain terrestrial plant macrofossils for AMS- ^{14}C dating, they became valuable archives for constructing a terrestrial $\Delta^{14}\text{C}$ calibration curve that takes into account the varying cosmogenic production rate of ^{14}C . Non-aquatic plant macrofossils derive their carbon directly from the atmosphere and are not affected by aquatic reservoir effects and older, carbonate-derived DIC in hard-water lakes. Pioneering ^{14}C -dated sediment varve chronologies were established for Soppensee, Switzerland (Hajdas et al., 1993) and Holzmaar, Germany (Hajdas et al., 1995). Similar dating efforts in Lake Gościąg, Poland (Goslar et al., 1995) and Lake Suigetsu, Japan (Kitagawa and van der Plicht, 1998) as well as in marine varves from Cariaco Basin (Hughen et al., 1998) followed soon after. More sophisticated sample treatments and varve recording brought the realization that uncertainties related to coring artefacts, indistinct varves and unrecognised hiatuses had introduced chronological uncertainties, some of which could be corrected during re-investigations (Hajdas et al., 2000; Hughen et al., 2006; Hajdas and Michczynski, 2010; Nakagawa et al., 2012).

Thus far only the varved sediments from Lake Suigetsu have demonstrated the potential for developing an exclusively terrestrial radiocarbon calibration curve across the entire age range back to the detection limit of ^{14}C -dating (Fig. 23) because Lake Suigetsu sediments uniquely contain terrestrial macrofossils beyond the onset of the Lateglacial (Bronk Ramsey et al., 2012).

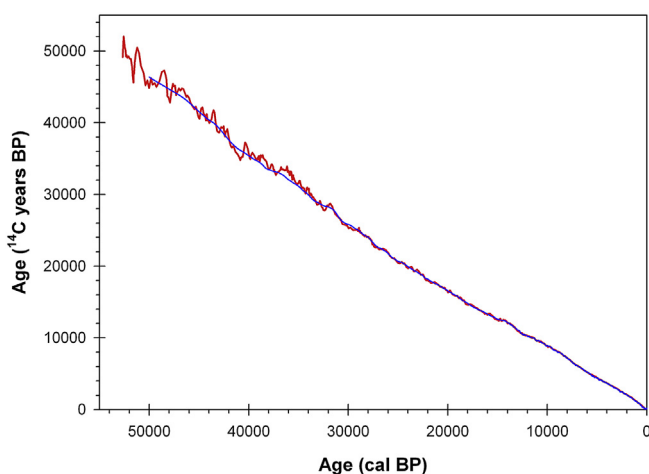


Fig. 23. Varve-calibrated radiocarbon ages of terrestrial plant macrofossils from Lake Suigetsu in Japan (red line; Bronk Ramsey et al., 2012) vs. IntCal13 calibration curve (blue line; Reimer et al., 2013). Data provided by T. Nakagawa and P. Reimer.

Global atmospheric variations in radiocarbon abundance over time can be exploited for comparative dating by so-called radiocarbon wiggle-matching, whereby synchronous and independent varve-counts and high-resolution ^{14}C chronologies are compared to best match the temporal pattern of radiocarbon abundance plateaus, declines and increases across the cosmogenic $\Delta^{14}\text{C}$ production record. Statistically optimised curve-fitting is typically used to anchor floating tree-ring records to the calendar-year timescale of the ^{14}C calibration curve (Kromer, 2009). Similarly, a ^{14}C calibration curve was successfully wiggle-matched with an early Holocene section of the Lake Kälksjön varve chronology from central Sweden around the 8.2 ka event (Snowball et al., 2010). Synchronisation of this varve record with the absolute ^{14}C timescale documented an unexpected ^{14}C reservoir effect of ca 350 years for Lake Kälksjön within a non-carbonaceous catchment area. The scarcity of terrestrial plant macrofossils in Lake Kälksjön had necessitated the use of bulk sedimentary organic matter for AMS ^{14}C dating. The observed ^{14}C reservoir effect in this case was attributed to lake internal or catchment-related remobilisation of older organic carbon and expressed multi-centennial variability during the Holocene (Stanton et al., 2010).

Radiocarbon wiggle matching as well as other objective ways to construct age–depth models can be replaced by statistical approaches of age modelling. Most common are Bayesian statistics (cf. Brauer et al., 2014) that combine complex statistical age distributions (as they often result from radiometric dating) with a mathematical sediment deposition-model (e.g. varve-based sedimentation rates) and develop statistically sound chronological information. For such statistics, the choice of the model is critical because its output depends on its design and on the quality of entered data (Brauer et al., 2014). Bayesian age modelling is an opportunity to combine different chronological data and integrate them with process understanding of the individual record to eventually provide a more precise age model. This approach was applied to a varved record from the Lateglacial in Scotland (two glaciolacustrine sites with 94 ± 4 and 259 ± 3 varve years) which were tied with six reliable radiocarbon dates and Bayesian age modelling to a floating calendar timescale (MacLeod et al., 2011). The Bayesian model used is constrained by the order of superposition of dated samples, their error ranges and the statistical matching between these chronological data and IntCal09 (Reimer et al., 2009). This age model indicates that the last glacier that occupied the Loch Lomond area (the Younger Dryas type locality in Scotland) achieved its maximum extent after ca 12.0 ka cal BP. The timing is consistent with a cooler period recorded by the NGRIP ice core (MacLeod et al., 2011). Another example applies Bayesian age modelling to the varved record of Soppensee in Switzerland (Blockley et al., 2008). After using the stratigraphical order of calibrated radiocarbon ages as a first constraint, additional information was incorporated into the Bayesian statistics such as relative varve age, sample depth and depositional models. This exercise resulted in a robust age model significantly improving the dating precision not only for varved but also for non-varved sections of Soppensee. Finally, the model accuracy was tested with the age of the Laacher See Tephra suggesting that Bayesian statistics can be used reliably to improve age–depth models (Blockley et al., 2008).

6.2. Reconstruction of Earth's magnetic field

Decadal to multi-millennial directional and intensity changes in the Earth's magnetic field are referred to as palaeomagnetic secular variation (PSV). Regional PSV signals are recorded in the positioning of sedimentary particles with magnetic properties and can be used for reconstructing the history of Earth's magnetic field, as well as for core-to-core correlation among sites. Similar to wiggle-matching, this enables validation of independent chronologies via cross-correlation

and to transfer a PSV-based chronology from a well-dated core (e.g. varved sediment) to a PSV-characterised core lacking stratigraphic control or containing non-laminated sediment (e.g. Alenius et al., 2008). Palaeomagnetic measurements can also quantify the global relative palaeointensity (RPI) while PSV declination and inclination changes provide a regional signal. RPI fluctuations over time can be used for correlation against well-dated global palaeointensity stacks or short-lived changes in field intensity, the so-called geomagnetic jerks (e.g. Snowball et al., 2007; Laj et al., 2013). RPI dating is applied to sedimentary records as well as to lavas and archaeomagnetic samples (e.g. Thompson and Oldfield, 1986).

The first PSV study on varve-dated lake sediment covered the last 4000 years in Elk Lake, Minnesota (Sprowl and Banerjee, 1989). PSV records from three Eifel maar lakes in Germany extend 13,000 years into the Lateglacial (Stockhausen, 1998). The stacked Eifel PSV record compares reasonably well to the PSV master curve in the UK that is based on three non-varved lacustrine records (Turner and Thompson, 1981). Differences between both stacks are attributed to uncertainty in ^{14}C dating of bulk organic matter for the UK master curve and to the low content of ferrimagnetic minerals such as magnetite in Eifel maar-lake sediments. In contrast, the sediment record from Meerfelder Maar in Germany hosts the best PSV record of all Eifel lakes due to its elevated content of ferrimagnetic minerals (Stockhausen, 1998).

Holocene clastic-biogenic varves in Fennoscandian lakes record a strong PSV signal. For example, Ojala and Tiljander (2003) recorded stable and strong PSV and RPI patterns in sediments from central southern Finnish lakes Alimmainen, Savijärvi, Korttajärvi and Nautajärvi and noted their mutual compatibility. Synoptic comparisons of PSV records with independent varve chronologies constrained the fidelity of varve counts, including varve counting error estimates, and yielded a stack of PSV inclination for the last ca 10,000 years. Snowball and Sandgren (2002) and Zillén and Snowball (2009) used similar approaches in Sweden for varved sequences in lakes Sarsjön, Frängsjön, Mötterudstjärnet and Furskogstjärnet. PSV signals in these Fennoscandian varved sediment sequences derive from primary (detrital) and secondary (*in situ* bacterial magnetosome) sources.

Stacking of PSV records from different sites generally improves the reliability of palaeomagnetic dating (Turner and Thompson, 1981; Stockhausen, 1998; Snowball et al., 2007). Stacking of palaeomagnetic data from the above-mentioned six annually laminated lake records from Finland and Sweden and one non-laminated sedimentary sequence resulted in a Fennoscandian PSV master curve (FENNOSTACK) and a RPI master curve (FENNORPIS) that are firmly linked to the year of sampling and boast a dating accuracy below $\pm 2\%$ (Snowball et al., 2007).

Palaeomagnetic dating via PSV (Haltia-Hovi et al., 2010) and RPI (Haltia-Hovi et al., 2011) of two lakes in Finland, Lehmilampi and Kortejärvi, took advantage of stratigraphic age control based on annually laminated sediments back to 5100 cal BP. RPI records from Lake Lehmilampi are compared with those of varved lakes Nautajärvi (Ojala and Saarinen, 2002) and Pohjajärvi (Saarinen, 1998), FENNORPIS (Snowball et al., 2007), absolute palaeointensity data from Europe and northern Africa (Kovacheva et al., 2009), as well as with the model output of CALS7K.2 for Northern Karelia (Korte and Constable, 2005). CALS7K.2 is a magnetic field model for the last 7000 years based on archaeo- and palaeomagnetic data that describes the global evolution of the geomagnetic field. The overall agreement shows that RPI data can be applied to transfer a chronology after correlating different natural archives (Fig. 24; Haltia-Hovi et al., 2011). The value of a well-dated sedimentary record, including palaeomagnetic data was exemplified by Stanton et al. (2010) when validating the varve record of Lake Kälksjön with FENNOSTACK. The authors localised significant errors in varve

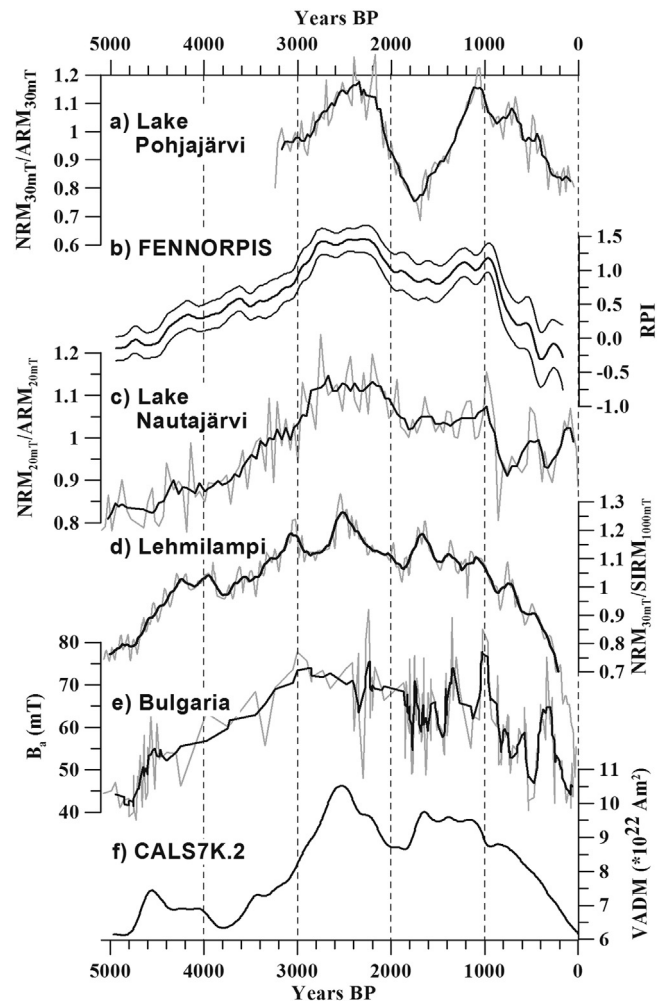


Fig. 24. Relative and absolute magnetic palaeointensity records from Europe for the last 5000 years with raw data (grey line) and a 5-point running average (black line). (a) Lake Pohjajärvi in eastern Finland (Saarinen, 1998); (b) FENNORPIS, a stack of seven Finnish and Swedish lakes (data shown with 95% confidence limits; Snowball et al., 2007); (c) Lake Nautajärvi in central Finland (Ojala and Saarinen, 2002); (d) Lake Lehmilampi in eastern Finland (Haltia-Hovi et al., 2011); (e) absolute palaeointensity data from Europe and northern Africa (Kovacheva et al., 2009). (f) The CALS7K.2 model output for Northern Karelia is plotted for comparison (Korte and Constable, 2005). Figure modified from Haltia-Hovi et al. (2011).

counting after comparing PSV records, high-resolution AMS- ^{14}C dates, ^{137}Cs profiles and the history of anthropogenic lead pollution. They concluded that ca 270 varves are either missing in Lake Kälksjön or have not been detected in the time interval dated after AD 1000. Moreover, ca 230 superfluous varves had been counted prior to 8000 cal BP (Stanton et al., 2010).

For the same site (Kälksjön in Sweden) a discrepancy between varve-dated palaeomagnetic and corresponding features temporally predicted by archaeomagnetic models has been discovered (Mellström et al., 2015). The reason for this temporal offset is a lock-in depth of the magnetic signal of up to 80 cm attributed to the high content of organic matter and the resulting low density of these sediments. Only varved sediments can provide information to detect and understand such effects (Mellström et al., 2015).

6.3. Solar forcing

Varve formation is assumed to be driven by climate and environmental factors that are in turn modulated by the intensity of

insolation. If that is the case, significant solar forcing of climate should be recorded in sufficiently long varve sequences (Anderson, 1961) in physical, chemical, or biological/fossil varve properties. In spite of radioactive decay of the cosmogenic isotopes ^{14}C and ^{10}Be , the adjusted abundances of ^{14}C and ^{10}Be in sedimentary records can theoretically be used in varved sequences as proxies for solar activity because sunspot numbers and the solar wind (among other factors, including the strength of Earth's magnetic field) modulate the intensity of cosmic ray irradiation and the production rate of cosmogenic isotopes. A more feasible approach for varved records is to detect periodicities in time series that can be matched to well-known solar cycles, like the 11-year Schwabe, the 22-year Hale or the 80–90-year Gleisberg cycles. Some of the pioneers studying clay varves in the early 20th century believed that solar forcing would have influenced melt water production from glaciers worldwide and thus exerted a global control on varve thickness. They surmised that the thickness of synchronously deposited varves should even be correlated between continents (De Geer, 1912, 1926), a hypothesis that was later discarded. Subsequent attempts to document solar cycles in annually resolved records were among the first modern varve-related climate studies (e.g. Glenn and Kelts, 1991). By predominantly utilising annual or seasonal lamination-thickness time-series, various frequencies have been detected that were associated with solar activity (e.g. Vos et al., 1997; Dean et al., 2002; Ojala and Alenius, 2005). However, physical links between solar activity and varve formation are mostly unproven and therefore remain disputed. Relative to the short time frame of modern instrumental recordings of climate change, the deep coverage of varve data through time provides valuable background information for solar physics (Bracewell, 1988). It remains challenging to distinguish between changes in cosmic/solar forcing and sedimentological thresholds affecting long varve records on millennial time scales. Although evidence for the influence of solar cycles is abundant in the geologic record throughout Earth's history (Algeo and Woods, 1994; Mingram, 1998; Shunk et al., 2009), it is difficult to ascertain annual cycles in pre-Quaternary laminated sediment when ^{14}C dating is no longer possible.

A comparison of the 2000-year varve thickness record of the Finnish Lake Lehmilampi with a tree-ring-based $\Delta^{14}\text{C}$ record suggests solar modulation of the climate system and of lacustrine sedimentation (Fig. 25; Haltia-Hovi et al., 2007). Periods of thicker varves at Lehmilampi coincide with lower solar activity, and thus with colder winters and longer periods of snow cover in northern

and central Europe. An extended snow cover (thickness, duration) causes more pronounced and higher discharge rates responsible for increased allochthonous sediment transfer and thus for an increased thickness of spring and early summer sublaminae.

The Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) are climatically characteristic periods within the last millennium expressing distinct associations with solar minima from Oort through Dalton (Fig. 25). Physical links may have been provided via changes in solar irradiance (especially UV radiation), altered atmospheric circulation patterns, and climate-sensitive ocean-atmosphere coupling in the North Atlantic (Haltia-Hovi et al., 2007). Individually or jointly these factors may account for the observed climatic variations. To further test and validate the suggested solar-sedimentary coupling with varves in Lake Lehmilampi, the abundance of the cosmogenic isotope ^{10}Be was investigated with annual resolution since AD 1900 (Berggren et al., 2010). Especially the last 100 years of the varved ^{10}Be record are valuable because it is accompanied by parallel annual ^{10}Be records from ice cores and some instrumental neutron and sunspot data (Fig. 26). Moreover, ^{10}Be is a valuable proxy for past solar activity due to its cosmogenic origin, short atmospheric residence time of up to one year, relative simple chemistry, and lack of anthropogenic sources (Berggren et al., 2010).

The sedimentary ^{10}Be accumulation rates for Lake Lehmilampi correlate with the 11-year Schwabe solar cycle and its amplitude throughout the investigated time period (Fig. 26). The observation of lower ^{10}Be deposition rates in varves during periods of higher solar activity (and vice versa) suggests a solar control mechanism, which is also indicated by simultaneous reductions of the atmospheric neutron flux and ^{10}Be deposition rates in the Greenland NGRIP ice core (Fig. 26; Berggren et al., 2009). The concentrations and deposition rates of ^{10}Be in varves agree for every solar cycle in spite of minor offsets in timing (Fig. 26), thus indicating that sedimentary ^{10}Be accumulation is indeed related to solar variability. This opens the possibility of using ^{10}Be profiling over depth as a tool for global synchronisation of palaeoclimatic sedimentary records (Berggren et al., 2010).

A combination of sedimentological, ^{10}Be and climate modelling data was used to analyse the time period of the well-documented 2800–2650 cal BP Homeric sunspot minimum in the varve sequence of Meerfelder Maar, Germany (Martin-Puertas et al., 2012). A sudden 2760 cal BP increase in varve thickness caused by diatom blooms (Fig. 27) was diagnosed based on proxies for (i)

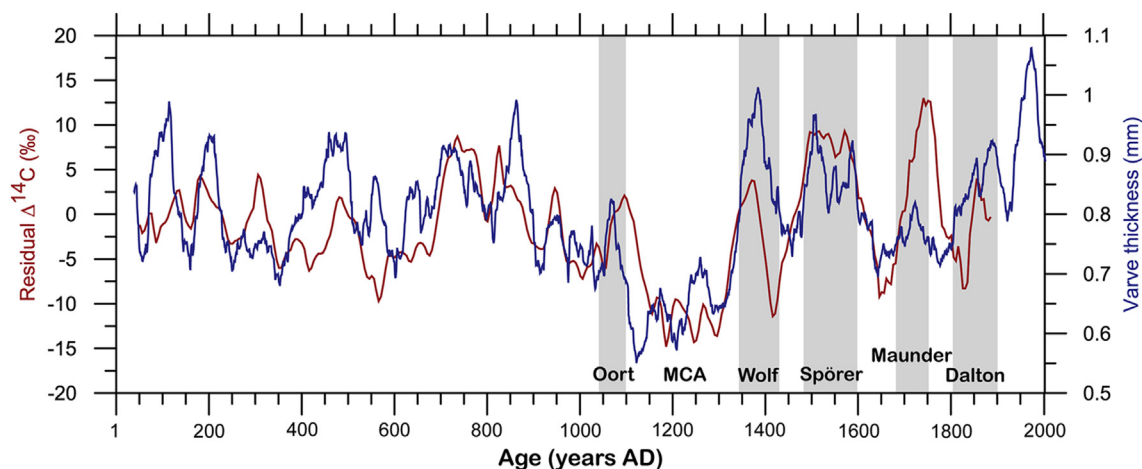


Fig. 25. Residual $\Delta^{14}\text{C}$ data on a 1000-year moving average (red line; Reimer et al., 2004) and varve thickness of Lake Lehmilampi in eastern Finland as a 51-year moving average (blue line). Phases of minimum solar activity are highlighted (Oort, Wolf, Spörer, Maunder and Dalton). The thinnest varves of the last 2000 years were deposited during maxima of solar activity, i.e. during the Medieval Climate Anomaly (MCA; modified from Haltia-Hovi et al., 2007).

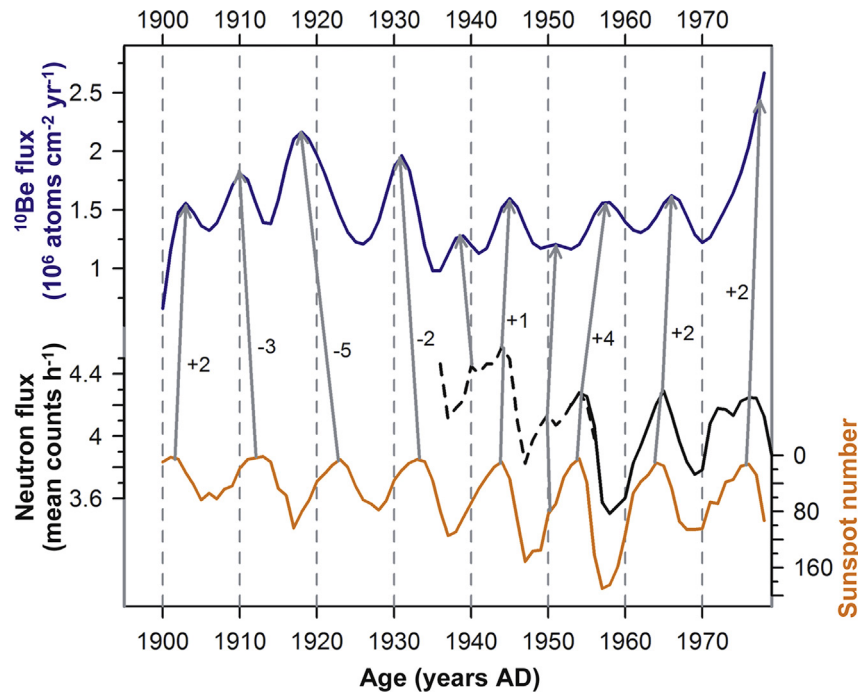


Fig. 26. Low pass filtered ^{10}Be flux rates (blue line) in Lake Lehmilampi (eastern Finland), instrumental neutron-flux data from 1953 to 1998 (black line) and data measured in an ionization chamber from 1936 to 1956 (dashed black line; McCracken and Beer, 2007) compared to sunspot numbers shown along a reversed axis (red line; data from Berggren et al., 2010). The grey lines with positive and negative numbers indicate the difference in years between sunspot and varve-dated ^{10}Be records.

lacustrine productivity and lake water circulation (sedimentological parameters, e.g. structure and varve thickness), (ii) allochthonous deposition (Ti abundance), and (iii) solar activity (^{10}Be accumulation rate). The interpretation suggests that stronger winds during the Homeric sunspot minimum enhanced water circulation and nutrient upwelling into the epilimnion, thus triggering diatom blooms and consequently increased varve thickness. Enhanced runoff as a source of nutrients can be excluded in the absence of elevated Ti abundance (Martin-Puertas et al., 2012). The doubling of the ^{10}Be accumulation rate and the simultaneous increase in spring windiness argues for a solar influence. The evidence for climate change from Meerfelder Maar links the Homeric solar minimum to intensified circulation in the troposphere. Stronger cosmogenic production of ^{10}Be during reduced solar activity has not only been recorded in Meerfelder Maar but also in Greenland ice cores and the same process simultaneously increased the content of cosmogenic ^{14}C in the atmosphere (Fig. 27).

Climate models suggest that the modern solar minimum causes an atmospheric pressure gradient that results in a trend towards more negative North Atlantic Oscillation (NAO) indices, lower temperatures, and intensified precipitation in late winter to early spring in central Europe (Martin-Puertas et al., 2012). Comparable solar forcing during the Homeric solar minimum would explain the palaeoclimatic changes detected in Meerfelder Maar and elsewhere in terms of cooling and increased humidity in western Europe (e.g. Holzhauser et al., 2005) when atmospheric circulation was influenced by negative NAO indices.

6.4. Accurate dating of events in Earth's history

Varved sequences can be affected by two fundamental types of sudden natural depositional events, namely (i) aeolian transport and deposition of pyroclastic tephra from explosive volcanic eruptions, and (ii) massive turbidite deposition (seismites, tsunamites) triggered by earthquakes that can also cause distortions of

the pre-existing laminated sedimentary structure. Other events like the emplacement of flood layers are discussed in later sections.

6.4.1. Volcanic ash layers

Varved sediment sequences are especially well suited for dating and analysis of volcanic ash layers (tephra). Due to the absence of bioturbation, rapidly deposited volcanic glass shards remain narrowly concentrated and in stratigraphic order for dating. Resulting regional tephrochronologies with dated individual volcanic marker layers are useful for validation of chronostratigraphies of other regional records that conserved the same isochronous tephra marker layers less accurately. Furthermore, even if tephra isochrones are chronologically floating without absolute age control, the availability of varved sediments between successive tephra layers indicates the time in varve years between volcanic eruptions (e.g. Brauer et al., 1999; Zillén et al., 2002; Van Daele et al., 2014). Technological advances made it possible to trace and identify thin isochronous laminae of volcanic ashes as cryptotephra, i.e. non-visible tephra, which typically comprise glass-shards or concentrations of volcanogenic crystals (Lowe, 2011), in late Quaternary sedimentary sequences thousands of kilometres away from their volcanic sources (e.g. Merkt et al., 1993; Schmidt et al., 2002; Zillén et al., 2002; Lane et al., 2011, 2012, 2013; Dörfler et al., 2012).

To provide an example, the 12,880 cal BP Lateglacial Laacher See Tephra (LST) and the 11,000 cal BP early Holocene Ulmener Maar tephra were detected and varve-dated in Holzmaar and Meerfelder Maar in the West Eifel volcanic field in Germany (Zolitschka et al., 1995; Brauer et al., 1999). The Ulmener Maar tephra is of regional importance for synchronisation of sediment sequences from Eifel maar lakes (Brauer et al., 2000), whereas the LST provides a more wide-spread time-marker for natural archives across Europe (e.g. Merkt and Müller, 1999; Lane et al., 2011, 2012; Wulf et al., 2013). The use of the LST and the onset of the Younger Dryas as anchor points for synchronising accurately dated varved sediment records is highlighted by a transect along three sites from western Germany to northern

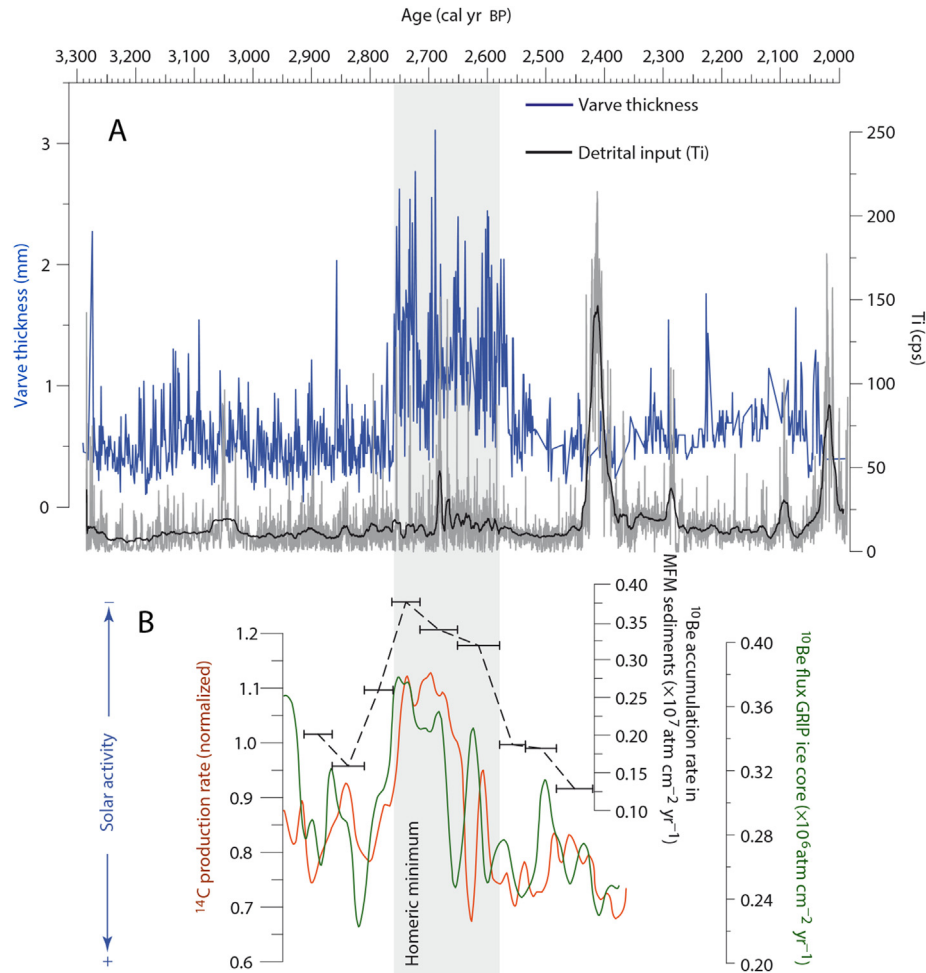


Fig. 27. (A) Varve thickness (blue) and variability of the titanium (Ti) abundance (in counts per second = cps, grey) as a proxy for detrital deposition close to the shaded Homeric minimum (3300–2000 cal BP) in Meerfelder Maar, Germany. The black line indicates smoothing with a 100-point running average. (B) Three independent proxies for solar activity: ^{10}Be accumulation rate in sediments of Meerfelder Maar expressed as flux (dashed black line; error bars indicate age uncertainty for each sample); normalised ^{14}C production rate as inferred from tree ring $\Delta^{14}\text{C}$ (red line; Muscheler et al., 2005; Reimer et al., 2009); ^{10}Be flux from the GRIP ice core (green line; Vonmoos et al., 2006). Figure modified from Martin-Puertas et al. (2012).

Poland (Fig. 28; Wulf et al., 2013). Similarly, the early Holocene Icelandic Vedde Ash layer was used to synchronise high-resolution records from Germany, Norway and Greenland (Lane et al., 2013).

Another example for the power of combining varves and tephras comes from Lago Grande di Monticchio in southern Italy. This lake is positioned downwind of the southern and central Italian explosive volcanoes and has accumulated more than 350 tephras during the last 135 ka (Wulf et al., 2004, 2008, 2012). Its detailed varve chronology provided chronological scaffolding for tephra occurrences (Zolitschka and Negendank, 1996; Allen et al., 1999; Brauer et al., 2007a) using direct $^{40}\text{Ar}/^{39}\text{Ar}$ dates for tephra layers from Lago Grande di Monticchio and matching ash layers with either historically known eruptions, or radiometric ages obtained for isochronous tephra layers at other Italian locations. An age model based on tephra layers alone was used to validate the independent varve and sedimentation-rate chronology resulting in a mean deviation of $\pm 5\%$ (Wulf et al., 2004). The accurately dated tephrachronology of Lago Grande di Monticchio was finally synchronised with regional marine tephra records (Wulf et al., 2008) to potentially provide independent age control without uncertainty by ^{14}C -reservoir effects for central and eastern Mediterranean marine (e.g. Paterne et al., 2008; Zanchetta et al., 2011) and terrestrial sedimentary records (Damaschke et al., 2013) where isochronous tephra layers can be geochemically identified.

Like Lago Grande di Monticchio, Japan's ca 150-ka-long varve record from Lake Suigetsu features ~30 visible volcanic ash layers that can be assigned to episodes of explosive volcanism in Japan and South Korea (V.C. Smith et al., 2013) and can potentially be used for correlation and synchronisation of continental and marine sedimentary archives within the region and beyond. The future development of Lake Suigetsu's cryptotephra record in addition to the existing record of visible tephras will further refine the tephrostratigraphic framework and yield a more complete picture of East Asian eruptive volcanic history and its influences on palaeoclimate.

Based on the tephra record of two lakes in the volcanically very active Chilean Lake District, an eruption record for the neighbouring Villarica Volcano have been determined and varve-dated (Van Daele et al., 2014). This record is unprecedented in continuity and temporal resolution, and documents 112 eruptions with a Volcanic Explosivity Index of ≥ 2 from Villarica Volcano for the last ca 600 years. Such data considerably improve the regional volcanic hazard assessments (Van Daele et al., 2014).

6.4.2. Earthquakes

Seismic and hydrographic surveys in lakes can bathymetrically detect large-scale mass-wasting scars resulting from earthquakes (e.g. Hilbe et al., 2011; Cukur et al., 2013). A well-preserved

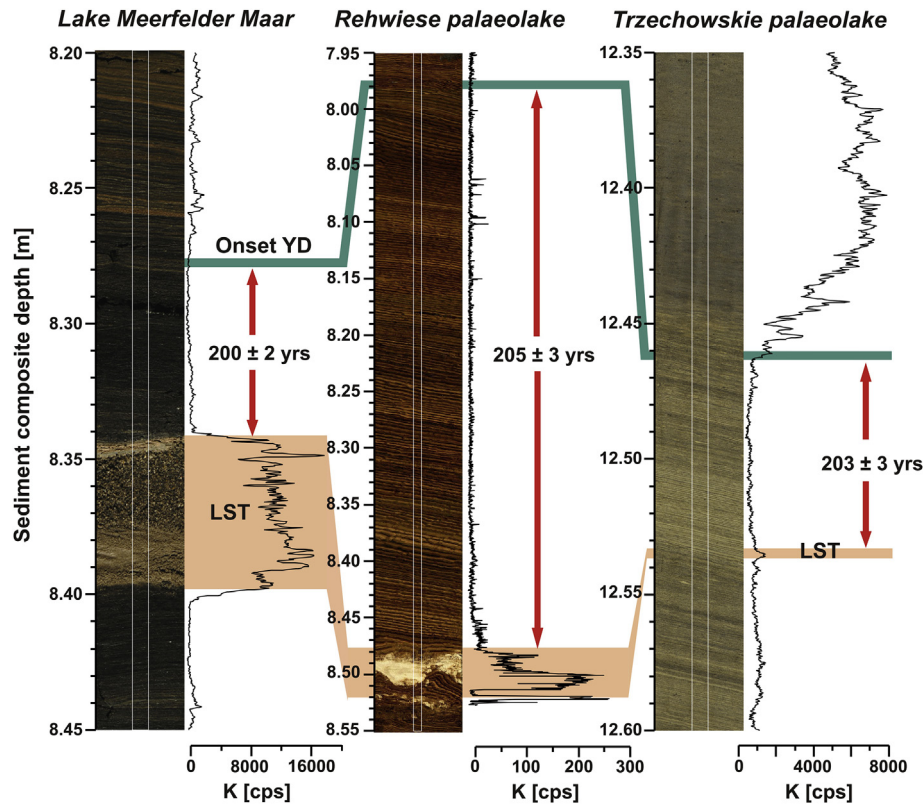


Fig. 28. Comparison of varved Lateglacial sediments from Meerfelder Maar (western Germany) with those from Rehwise palaeolake (north-eastern Germany) and Trzechowskie palaeolake (northern Poland) documenting the position of the Laacher See Tephra (LST) and its temporal relation to the onset of the Younger Dryas (YD). Note the increase of potassium (K) abundance at the position of the LST for all sites as documented by μ XRF core scanning. The white box in the centre of each image is related to the area analysed by XRF scanning (modified after Wulf et al., 2013).

stratigraphy of varve sequences provides highly sensitive recorders of strong seismic activity and seismically triggered turbidite occurrences, whereas it is mostly impossible to detect palaeo-earthquakes and turbidites in non-laminated sedimentary records. Moreover, varve-dated sequences can provide information about intensity and timing of these seismic events. As an example, seismic mass wasting deposits in Lake Bramant in the French Alps were chronologically constrained by the lake's varve-dated sedimentary record and tentatively assigned to a nearby historic 19th century earthquake with a magnitude (Richter) of M 6.0–6.5 (Guyard et al., 2007).

A strong regional seismic event like the AD 1960 Valdivia earthquake, i.e. the strongest earthquake ever recorded on Earth with a magnitude of M 9.5, is clearly discernible in varved sediments of Lago Puyehue in southern Chile as massive mixed layers (seismites) intersected between annual laminations (Boës and Fagel, 2008). Also in the Chilean Lake District lacustrine turbidites interrupting a varve sequence are interpreted as a palaeoseismic record, which is regarded as a tool for quantitative earthquake reconstruction (Moernaut et al., 2014).

Even M 5.5–6.0 events have been recorded in Swedish varves (Mörner, 2011) based on structural changes of laminations near the water–sediment interface. Seismic shaking results in temporary liquefaction of unconsolidated and water-rich sediment, shallow re-suspension, and rapid re-deposition as seismites. The loss of structure can be accompanied by lateral flow and 'flaming upwards' structures (Migowski et al., 2004; Mörner, 2011). Within the Swedish Late-Pleistocene and early Holocene varve chronology, 59 seismic events were recorded with estimated magnitudes of M 7–8 (Mörner, 2011), while 53 seismites were recognised within Israel's

varved sedimentary Dead Sea record relating to earthquake magnitudes of ca M 6.0–6.5 (Fig. 29A; Migowski et al., 2004). Also in the tectonically active region around Lake Van (eastern Turkey) seismically induced deformation structures are frequent. They are easy to recognise in the varves of Lake Van and occur as mixed clayey silts, mass-movements or liquefaction structures and folded or overturned layers (Fig. 29B; Stockhecke et al., 2014).

6.5. Climate and environmental reconstruction

Palaeoclimatic and palaeoenvironmental reconstructions based on varved lake sediment-records were revolutionised in a two-step process. The introduction of freeze-coring in the 1970s allowed recovery of undisturbed topmost varves from modern lakes (e.g. Shapiro, 1958; Swain, 1973; Saarnisto, 1979a; Renberg, 1981b) and made the reliable counting of varves down core possible beginning with the year of coring. The resulting, accurately varve-dated sediment records contained valuable environmental proxies that were urgently needed to address growing concerns about anthropogenic pollution and degradation of lake ecosystems. Sufficiently long varved sediment records were uniquely positioned to provide annually resolved estimates of human impact and natural background levels. The growing overlap of synchronous instrumental and varve-based data also provided statistical weight to calibrate proxies for improved interpretations (e.g. Bradley et al., 1996).

The second major step forward in the 1990s coincided with the advance of ice core studies that greatly enhanced the interest in long archives with high temporal resolution (Dansgaard et al., 1993). Varved sedimentary records were soon applied to constrain the duration of palaeoclimatic events and associated rates

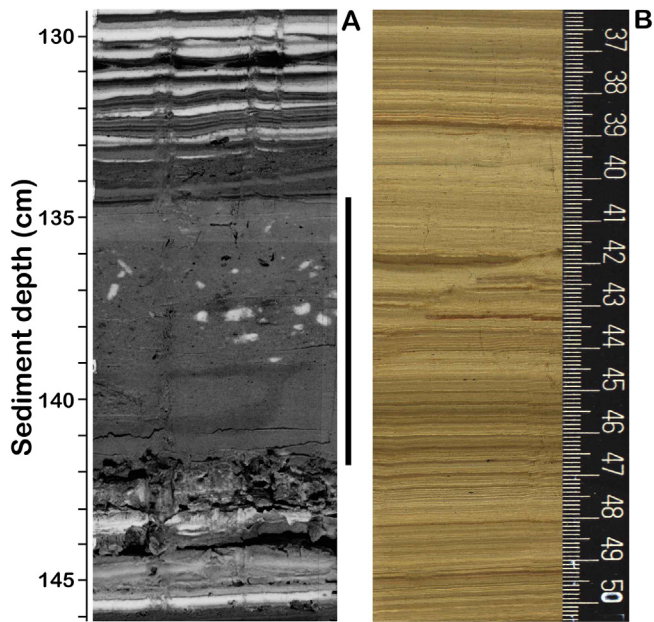


Fig. 29. (A) Example of a varved sediment sequence disturbed by an earthquake from the Dead Sea in Israel (cf. Fig. 5). The record comprises laminated clay-sized clastic sediments (dark sublaminae) and authigenic aragonite and gypsum (pale sublaminae). This pattern is punctuated by sedimentary event layers (seismites) consisting of aragonite fragments floating in a silty detrital matrix. The components were fluidized, brecciated, re-suspended and then re-settled during and after the earthquake of AD 1033 (black bar between 134.5 and 142 cm; modified after Migowski et al., 2004). (B) Biochemical Holocene varves of Lake Van (Turkey). In particular due to the finely laminated clayey silt a seismically induced deformation structure is apparent between 41.5 and 43.5 cm section depth (modified after Stockhecke et al., 2014).

of change, followed by the ongoing development of high-resolution and continuous sediment logging and other advanced techniques that provide a wealth of data with up to sub-annual resolution.

6.5.1. Human impact

Records of anthropogenic environmental change are typically well preserved in varved lake sediments. They are expressed as shifting palynological and diatom assemblages due to impacts on land use and resulting changes in primary lacustrine productivity (e.g. Voigt et al., 2008; Dreibrodt and Wiethold, 2015), in the form of increased accumulation rates (Zolitschka, 2002), and as

deposition of heavy metals in lakes (e.g. Lottermoser et al., 1997; Brännvall et al., 2001; Sun et al., 2006). A clearly detectable long-term shift in varved sediment records reflects soil evolution in catchment areas and the supply of allochthonous mineral matter (e.g. Ojala and Alenius, 2005). Following an early Holocene stabilisation of European soils and vegetation, natural erosion and particle fluxes into lakes were initially rather limited. Anthropogenic disturbance of natural environments via deforestation and agricultural land use sometimes increased sediment transport into lakes by an order of magnitude, as observed at Holzmaar ca 2800 years ago (Fig. 30; Zolitschka, 1998) and at Belauer See ca 2200 years ago (Dreibrodt and Wiethold, 2015), both in Germany. For the same reason, an abrupt shift in sedimentation affected Fayetteville Green Lake in the USA at the beginning of the 19th century when deforestation by European settlers resulted in a 7-fold increase in accumulation rates, enhanced nutrient flux, and elevated lacustrine productivity, i.e. cultural eutrophication (Hilfinger et al., 2001).

The degree of heavy metal pollution, another indicator of human impact, is difficult to assess if it only relies on elemental concentrations instead of considering the changes in SAR and dilution by e.g. an increase of catchment-derived minerogenic matter (Meriläinen et al., 2010). For instance, the substantial variability of natural trace metal concentrations in lake sediment over the course of several millennia (Augustsson et al., 2010) has to be interpreted in terms of changes in accumulation rates and thus underlines the significance of varved sediments for a meaningful interpretation of heavy metal variation.

Varve records have been used to deconvolute pollution signals deriving from both industrial activity in the catchment area and longer-distance atmospheric fallout (Brännvall et al., 2001; Hilfinger et al., 2001; Meriläinen et al., 2010). Human activities have generally increased the fluxes of toxic and other trace metals into natural environments (Nriagu, 1996). For example, mercury (Hg), lead (Pb) and cadmium (Cd) bore witness to the obvious and widespread anthropogenic increases in pollution during the past 150 years (Augustsson et al., 2010). However, much earlier ore mining and metal smelting had contributed to air pollution and noticeable widespread heavy metal deposition as reported by early investigations of Greenland ice cores indicating pre-industrial atmospheric trace metal contamination affecting even remote regions (Renberg et al., 1994). According to historical sources, lead was one of the first metals to be anthropogenically emitted into the environment during processing of sulphidic silver and lead ores (Nriagu, 1983). Atmospheric Pb pollution can be traced back

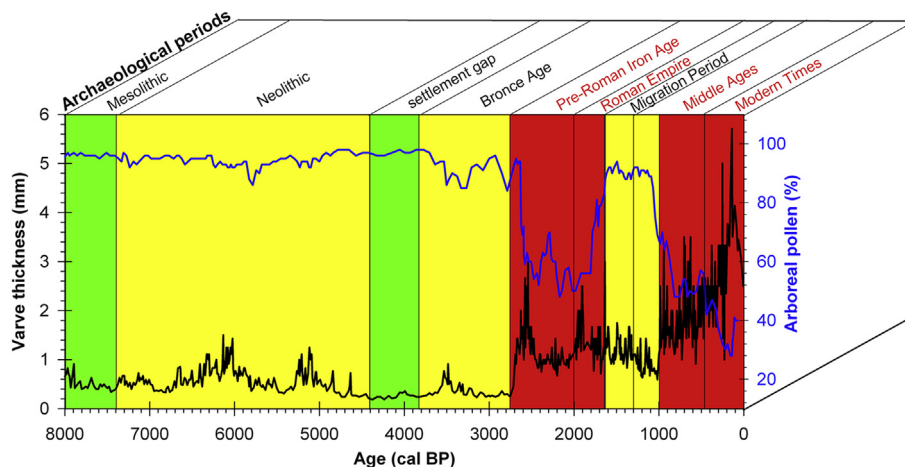


Fig. 30. Varve thickness in Lake Holzmaar, Germany vs. human impact indicated by arboreal pollen content during archaeologically defined periods. Periods of high human impact are marked in red, periods of low human impact in yellow and those with insignificant human impact in green (data from Zolitschka, 2002).

ca 4000 years in high-resolution varve records (Renberg et al., 2000). The first distinct Pb peak in history was deposited during Roman Times around 2000 years ago, followed by lower deposition rates during the Migration Period (AD 400–900) and a significant increase since AD 1000 with varve-dated maxima around AD 1200 and 1530 when mining and metal production increased significantly in Europe. Atmospheric lead pollution increased a second time with the onset of industrialisation. Distinct Pb reductions at ca AD 1924 and 1950 coincide with economic crises after both world wars, whereas a maximum in the early 1970s coincides with the peak use of leaded gasoline. Since then, environmental legislation in Europe and elsewhere contributed to decreased Pb emissions that have been accurately recorded in many varved lakes (Lottermoser et al., 1997; Renberg et al., 2000; Brännvall et al., 2001; Stanton et al., 2010; Dörfler et al., 2012).

Accurate dating of fluctuations in polluting Pb concentrations in four high-resolution varved Swedish lake records provided temporal information about Pb emissions from pre-industrial to modern conditions (Fig. 31; Brännvall et al., 1999, 2001). Lead is an excellent indicator for airborne pollution because it is chemically immobile in natural sedimentary archives, easy to analyse, and can be characterised isotopically (e.g. $^{206}\text{Pb}/^{207}\text{Pb}$) to potentially distinguish natural local Pb sources in the catchment area from airborne Pb pollution of a distant origin (Brännvall et al., 2001). Varved sediments in the Pettaquamscutt River basin in Rhode Island, USA witnessed a change in the $^{206}\text{Pb}/^{207}\text{Pb}$ ratio corresponding to the mining and smelting of Pb ores in the Upper Mississippi Valley district that accounted for almost all Pb production in the USA at the time of the isotopic shift (Lima et al., 2005). This isotopic event potentially provides a stratigraphic marker for sediments deposited in the past 200 years in north-eastern North America.

All potential dating tools relying on airborne transport of pollutants are limited to areas that are located not too far downwind

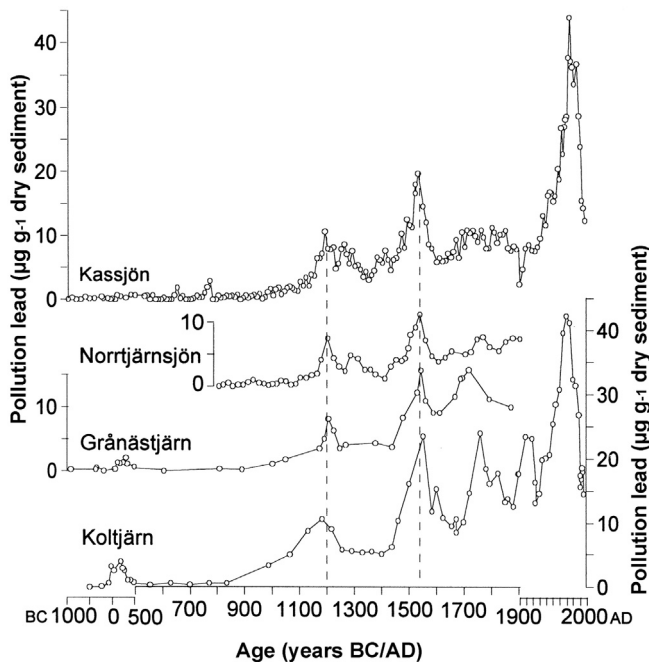


Fig. 31. Concentrations of pollution lead in sediment from four varved Swedish lakes plotted against varve-dated calendar-year timescales. The patterns indicate increases in lead concentrations in Roman, medieval and modern times. Lake Norrtjärnsjön has a floating chronology and was 'wobble-matched' against the other three records using lead isotope variability (dashed vertical lines). Note discontinuities along the time scale (modified after Brännvall et al., 1999).

from point sources. For instance, a varve-dated Arctic record from Svalbard shows a pollution pattern comparable to European records until AD 1970. Thereafter, anthropogenic Pb fluxes increased for the following two decades as a consequence of local coal combustion on Svalbard (Sun et al., 2006).

Heavy metal pollution in lacustrine varves can also be distinctly local if mining activities were carried out in the vicinity of the lake and caused far higher pollutant accumulation rates compared to pollution levels reached via long-distance aeolian transport as in examples from Sweden (Brännvall et al., 2001). Local lacustrine pollution can often be linked to historically or archaeologically known nearby mining sites. Regional and local mining activities in the area of varve-dated sediments in Lake Bramant in the French Alps are recorded by elevated copper contents during the early Bronze Age (BC 1920–1820) and by peaks in lead and copper for the Roman Empire (AD 115–330; Guyard et al., 2007). Copper pollution of Portage Lake in Michigan, USA, closely reflects the discharge history of nearby copper mills that had been active from AD 1850 until 1968. Copper mine tailings were dumped into the lake and temporarily created artificially varved lake sediments until the pollution abated after AD 1968 (Kerfoot et al., 1994). Metal concentration and flux profiles in Portage Lake produce fundamentally different patterns where only the flux profile corresponds to the historic record of pollution. Such interpretation would be impossible in non-varved sedimentary sequences without detailed knowledge of sedimentation rates.

A different type of human impact on a lacustrine varve record has been reported for Lake Butrint in Albania where down core shifts in carbon stable isotope values ($\delta^{13}\text{C}$) of bulk organic matter and of authigenic carbonate indicate increasing eutrophication for the second half of the 20th century, in agreement with historical and instrumental data (Ariztegui et al., 2010). Intensified agriculture and the use of freshwater for irrigation in the catchment area are responsible for reduced freshwater input and/or enhanced seawater inflow into this lake from the nearby Mediterranean Sea, thus increasing the salinity of lake water as witnessed by increasing $\delta^{18}\text{O}$ ratios of authigenic carbonates. Increased salinity is also reflected by a distinct change in carbonate mineralogy from dominantly low-Mg calcite to aragonite in AD 1943 (Ariztegui et al., 2010).

Groundwater overexploitation for agricultural purposes and related salinization of arable land in catchment areas changed the calcareous varves of two maar lakes in Central Mexico (Kienel et al., 2009). Anthropogenic influence after AD 1940 caused and accelerated precipitation of aragonite at Hoya la Alberca and of halite at Hoya Rincón de Parangueo as indicators of closed basins with high evaporative stress.

Varve preservation can also be the result of increasing eutrophication. Varves of Baldeggersee in Switzerland began to be preserved in the late 19th century mainly due to increased phosphorous input and disappeared after the onset of artificial oxygenation of the hypolimnion in the late 20th century (Wehrli et al., 1997).

6.5.2. Climate reconstruction

The nature of palaeoclimatic reconstructions based on annually laminated sediments strongly depends on the type of varves. Clastic and clastic-biogenic varves convey hydroclimatic information about the transfer of minerogenic matter by precipitation and downstream sediment transport from the catchment area into the lake basin (e.g. Hardy et al., 1996; Ojala and Alenius, 2005; Cockburn and Lamoureux, 2008). In contrast, organic and some other types of varves store a variety of biological proxy information that enables qualitative and quantitative palaeoclimatic reconstructions based on fossil remains like pollen, plant

macrofossils, charcoal, non-pollen palynomorphs, diatoms, and chrysophyte cysts, as well as chironomids, coleoptera, ostracods and cladocera (Smol et al., 2001a,b). Finally, endogenic varves are distinguished by precipitated minerals such as calcite that can constrain palaeo-geochemical changes in lake water and may support stable isotope analyses. Altogether, diverging varve records from many different regions on Earth make available a wide variety of reconstructions that may include temperature, precipitation or wind intensity. Additionally, some reconstructions provide insight into complex phenomena of ocean-atmospheric circulation patterns such as the El Niño Southern Oscillation (ENSO) or the North Atlantic Oscillation (NAO). These topics will be considered in greater detail in the following sections.

6.5.2.1. Hydroclimatic conditions. Efforts to quantitatively understand the formation of clastic varves focus on contemporary processes that control the seasonal sediment delivery to lake basins. In particular, the Arctic lends itself to this type of study because its pristine environments reflect a climatic signal that is only marginally influenced by human activities (Cockburn and Lamoureux, 2008). Multi-year sediment trap studies in the Canadian Arctic examined the relationship between climate, runoff and sediment deposition. Although these studies have emphasised seasonal mass accumulation as the main proxy for runoff via melting of snow and glaciers or precipitation, other investigations regard grain size as a useful sedimentary parameter to evaluate past hydroclimatic conditions (Francus et al., 2002). A test for these parameters was implemented in Cape Bounty West Lake in Nunavut, Canada to explore the seasonal relationship between hydroclimatic processes and physical sedimentation, and to document the texture of seasonal deposits from AD 2003–2005 melt seasons (Cockburn and Lamoureux, 2008). Highly turbid pulses of relatively coarse sediment were rapidly delivered by underflows to the bottom of West Lake. However, transport at times of persistently low discharge and reduced load of suspended sediment was exclusively performed by homopycnal plumes distributing smaller particles across the lake. Thus, grain size in a depositing varve is a function of the character of the inflowing sediment load and can be decoupled from mass accumulation rates (Cockburn and Lamoureux, 2008).

The examination of clastic-biogenic varves in central southern Finland by Tiljander et al. (2002) and Ojala and Aalenius (2005) demonstrated that the accumulation of mineral sublaminae within varves provides a proxy record of winter precipitation and temperature as increased runoff during spring enhances erosion in the catchment (Ojala et al., 2013). The intermittent analysis of long varve records with seasonal resolution indicated that the winter/spring climate has changed considerably and repeatedly during the Holocene with characteristic periods of milder and wetter winters around BC 7000 and AD 1000–1200 (i.e. the MCA) and increased spring runoff and catchment erosion occurring around BC 5400–5200, 2700–2400 and BC 1500 to AD 500. However, due to local disturbances of the varved record it remains challenging to demonstrate a direct link between varve characteristics and modern instrumental weather observations. For example, only 34% of the variability in the AD 1880–1993 varve data from Lake Nau-tajärvi can be explained by winter precipitation and the temperature of the spring melt season (Ojala and Aalenius, 2005). The monitoring of sediment traps, comparisons of multi-site varve records from geographically limited areas, and subsequent statistical evaluations are likely the best strategy to improve proxy utilisation for quantitative reconstruction of palaeoclimate from varved records beyond the instrumental period.

6.5.2.2. Palaeoflood events. For inhabited regions the observed increase in frequency and intensity of extreme flood events is

important to address future flood risks (Schillereff et al., 2014). As river-gauge records and historic data are too short to display any longer-term trends, other sources need to be tapped in order to acquire palaeoflood records. In a comprehensive review Schillereff et al. (2014) discuss the related processes, the proxies available and the challenges that often restrict a robust interpretation. Finally, they suggest a conceptual model for palaeoflood analysis and state that varved sediment records are particularly useful for this approach. Moreover, the flood layers are usually quite different in composition from the seasonal successions of layers and thus are easier to distinguish.

Several central European varved lake records have been used empirically for reconstructions of palaeoflood events in spite of a considerable lack in understanding of the processes that control the deposition of flood layers. Nevertheless, the continuous nature and high temporal resolution of some varved lake sediments in the European Alps provided archives of natural flooding. Flood events are characterised by minerogenic layers with contrasting chemical and mineralogical composition that are intercalated into regular lacustrine varved sediments. Flood layers are detectable by a variety of methods including microfacies analysis for determining the season of flooding. Scrutiny of longer records can yield highly resolved flood catalogues spanning centuries to millennia that can be partly matched and calibrated with instrumental and historic data (Czymzik et al., 2010, 2013; Swierczynski et al., 2012; Wirth et al., 2013a; Corella et al., 2014). A palaeoflood record from varved sediments of Ammersee in southern Germany used seasonal climatic and environmental information and calibration against instrumental runoff data from AD 1926–1999 to reconstruct palaeofloods for the last 450 years (Czymzik et al., 2010). Microstratigraphic positions of flood layers within annual depositional cycles demonstrated that flooding occurred exclusively during spring and early summer. The alpine hydroclimatic conditions for flooding seem to be controlled by interplay between different synoptic weather situations and exhibit evidence for orbital and solar forcing (Fig. 32; Czymzik et al., 2010, 2013).

The varved sediments of Mondsee in Austria feature intercalated detrital layers related to heavy rainfall and provide an archive for the reconstruction of extreme hydrological events of the last 1600 years (Swierczynski et al., 2012). It was concluded that the local flood frequency is likely modulated by the combined influence of zonal and meridional circulation modes, and that there is no simple relation between flood frequency and climatic change.

The varved record of Lago di Ledro in the Southern Alps of northern Italy was used to reconstruct flooding with seasonal resolution for the last 2000 years (Wirth et al., 2013a) and placed flooding predominantly into summer and autumn. An enhanced occurrence of summer flooding during solar minima suggests solar-induced circulation changes resembling negative conditions of the NAO as a controlling atmospheric mechanism for flooding (Wirth et al., 2013b). Moreover, high-resolution geochemical and sedimentological analyses of the varved sediment record from Montcortés Lake (north-eastern Spain) document extreme rainfall events since the 14th century AD (Corella et al., 2014).

6.5.2.3. Precipitation. Sedimentological archives that are only indicative of rainfall are relatively rare. The stored water content in soils and vegetation in most catchment areas can provide continuous runoff even in the absence of precipitation, except in arid and semi-arid areas. The varved sediment of Lake Yoa is located in a hyper-arid region of the African Sahara in northern Chad (Kröpelin et al., 2008; Francus et al., 2013a). The varve-based palaeo-environmental reconstruction documents progressive environmental deterioration since 6100 cal BP indicated by gradual changes from tropical to drought-tolerant desert vegetation, a lake-

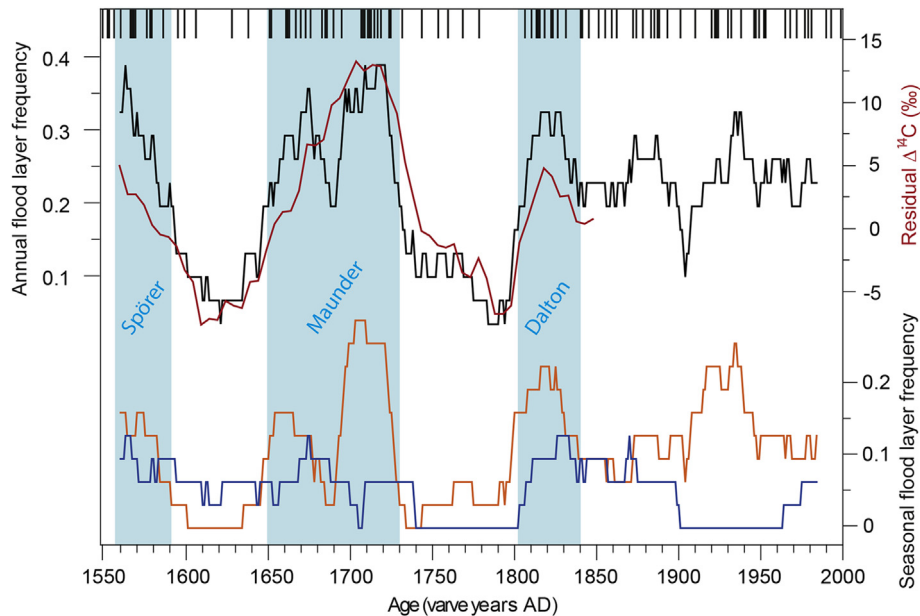


Fig. 32. Flood layers (solid bars) and annual flood-layer frequency (black line representing a 31-year running mean) from the varve-dated record of Ammersee in Germany compared with residual $\Delta^{14}\text{C}$ (red line representing a 1000-year running mean; Reimer et al., 2004). Spring (blue line) and early summer (brown line) flood-layer frequencies (31-year running means) express maxima for periods with low solar activity marked by the Spörer, Maunder and Dalton solar minima (blue bars; modified after Czymzik et al., 2010).

level decline resulting in hypersalinity, and the development of a reed swamp along its shorelines. The combined data indicate a reduction in regional annual rainfall from ~250 mm around 6000 cal BP to <50 mm since 2700 cal BP. The varves also document the abrupt change from a hydrologically open lake to a closed lake when salinity was rapidly increasing.

Under humid conditions and in high altitudes, where vegetation and soils are much less important for runoff control, precipitation signals can be preserved in sedimentary records such as Oeschinensee in the Swiss Alps (Amann et al., 2014). Based on proxy–climate correlation it was concluded that 40–50% of varve thickness can be explained by variations in summer precipitation for the last century. Rainfall is transferred to the varves via enhanced sediment flux resulting in thicker and more siliciclastic varves.

For Cape Bounty East Lake in the Canadian High Arctic, Lapointe et al. (2012) analysed annual grain-size variations with an innovative image analysis system. They concluded that the varve-dated coarse grain-size record (98th percentile) is correlated with summer rainfall as documented by instrumental data from a near weather station. Surprisingly, changes in particle-size distribution are only weakly correlated with varve thickness measurements pointing out for the need of a good understanding of processes when reconstructing precipitation (Lapointe et al., 2012).

Southern-hemispheric winter precipitation was reconstructed back to AD 1530 based on varves in proglacial Lago Plomo in the Chilean Andes (Elbert et al., 2012). As a first step, AD 1930–2002 meteorological data were used to develop and calibrate a mechanistic model for clastic varve formation and mass accumulation rates in relation to winter precipitation.

The varve thickness in the southern-hemispheric Lago Puyehue in Chile is controlled by enhanced diatom productivity during austral winter when strong westerly winds in combination with precipitation intensify lacustrine circulation and provide nutrients for algal growth (Boës and Fagel, 2008). Correlation of varve thickness with AD 1980–2000 instrumental meteorological data demonstrated that varve thickness is closely linked to precipitation and increases during rainfall events in winter. Thin varves point to

precipitation deficits during El Niño years (Boës and Fagel, 2008) and suggest Lago Puyehue as a potential archive for palaeo-El Niño reconstructions. Spectral analysis of the Lago Puyehue varve thickness record reveals periodicities consistent with hemispheric or even global climate oscillations (Fagel et al., 2008) and is consistent with data from Saanich Inlet on the Canadian west coast (Dean and Kemp, 2004).

A record of tropical South American precipitation is preserved in authigenic calcites in the high-altitude varved Laguna Pumacocha in the Peruvian Andes (Bird et al., 2011) where $\delta^{18}\text{O}$ of lake water reflects the short-term variability in $\delta^{18}\text{O}$ of precipitation, which in turn is recorded by $\delta^{18}\text{O}$ of authigenic calcite precipitated from the water column. Three time slices stand out within the resulting 2300-year high-resolution record of South American summer-monsoon intensity, namely (i) an AD 900–1100 dry period during the MCA, (ii) an AD 1400–1820 wet period during the LIA and (iii) a return to more arid conditions since AD 1900 (Bird et al., 2011).

6.5.2.4. Temperature. Hardy et al.'s (1996) pioneering field study in the Canadian Arctic to connect temperature-controlled sediment supply with varve deposition was followed by more detailed examinations of underlying physical control mechanisms (e.g. Hughen et al., 2000; Moore et al., 2001). With the advent of sophisticated statistical software tools it became possible to link modern climatic conditions and their biological manifestations in lacustrine and surrounding terrestrial environments to past climatic conditions. The urgent question of whether temperature recorded for the last 100 years exceeds longer-term natural variability can be addressed by using a variety of temperature-sensitive microfossil assemblages for high-resolution temperature reconstructions beyond the onset of instrumental data recording.

A quantitative expression of the relationship between air temperature, discharge, and suspended sediment transport was developed for Lake C2 on northern Ellesmere Island in Canada (Hardy et al., 1996). The algorithm and AD 1950–1992 meteorological data were used to hindcast suspended sediment transport, which compared well to the observed varve thickness record. One suggested explanation is that varve thickness can be used as a

proxy for summer temperature, assuming that the intensity of summer-time warming entirely controls the amount of runoff. Another option suggests that this signal is driven by precipitation as rain (summer) or snow (winter). The latter might have increased the storage of water and consequently created higher discharge rates. More recent studies on locations with less extreme Arctic climate indicate that a lack of snow after snowmelt complicates interpretation of some varve records in strictly snow fed watersheds (Cockburn and Lamoureux, 2008).

The variation in varve thickness in the proglacial Lake Hvítárvatn of the Icelandic Arctic depends on the available amount of melt water from Langjökull glacier to transport erodible minerogenic matter to the lake. Lake Hvítárvatn provides a detailed 3000-year varved record of glacial activity of Langjökull (Larsen et al., 2011). Langjökull's aerial extent determines when minerogenic debris is more abundant to yield thicker varves. An increase in sedimentation rate in Lake Hvítárvatn beginning in the 14th and 15th century (Fig. 33) is consistent with cooling during the LIA in Iceland (Geirsdóttir et al., 2009). Varve thickness finally decreased at the beginning of the 20th century coinciding with glacial recession after termination of LIA and the onset of 20th century warming (Fig. 33).

The same Lake Hvítárvatn varve record witnessed the transport and deposition of ice-rafted debris (IRD) during intervals when one of the outlet glaciers advanced into Lake Hvítárvatn and maintained an active calving front. Sediment-laden icebergs floated across the lake and released clasts upon melting. Although IRD deposition was highly stochastic, the IRD flux roughly reflects the volume of icebergs over time and can be used to infer changes in iceberg production (Fig. 33). Increased IRD deposition began around AD 1760 in response to summer cooling to levels not experienced during the previous more than 2700 years and indicates that this advance represented Langjökull glacier's Holocene maximum (Larsen et al., 2011). The glacier maximum extended from AD 1820–1940 and reflected continuous presence of the calving glacier margin while IRD declined after AD 1890 marking the retreat of the outlet glaciers from Lake Hvítárvatn.

Another proglacial varve record (Trüebsee, Central Swiss Alps) established a close relationship between independent temperature

reconstructions based on tree rings and varve-dated particle-mass accumulation rates (Glur et al., 2015). This comparison indicates that strong links exist between summer temperature, advance or retreat of a glacier in the lake catchment-area and accumulation rates obtained from lacustrine sediments. Moreover, major glacial advances are reconstructed via high mass accumulation rates for the periods of the Dalton, Maunder, Spörer and Wolf solar minima (Glur et al., 2015).

High-resolution chironomid-inferred temperature reconstructions for the last millennium were extracted in the European Alps from varve-dated sediment records of Lake Silvaplana and Seeburgsee in Switzerland. These temperature reconstructions compare well with local and regional instrumental records for the last century (Larocque-Tobler et al., 2012) and are statistically consistent with reconstructions obtained from local Alpine regions and the Northern Hemisphere (Fig. 34). The MCA was 1.2 °C warmer and the LIA 0.5 °C colder than the average 20th century during which temperatures increased by 0.8 °C. Extending this approach to a multi-archive reconstruction of summer temperatures for the European Alps, Trachsel et al. (2012) covered the last millennium with nine different calibration approaches including chironomids, sediment geochemistry and tree ring data (Fig. 34). At another varved site (Lake Zabinskie, north-eastern Poland) a comparison between chironomid-inferred mean August temperature and instrumental data since 1896 AD shows excellent agreement ($r = 0.91$; Larocque-Tobler et al., 2015). This study highlights the potential of chironomid-based climate reconstruction with annual or near-annual resolution based on varved lake sediments.

Organic geochemistry offers temperature-sensitive biomarker approaches to obtain palaeotemperature reconstructions from high-resolution varved sediment records. Although the long-chained alkenone unsaturation index ($U^{k_{37}}$) is mainly known for its use in marine palaeotemperature reconstruction (e.g. M. Smith et al., 2013), studies for limnic systems suggest that this method can also be used as a temperature proxy for lakes if appropriate calibrations are applied (Chu et al., 2005b; Sun et al., 2007; Liu et al., 2011). For example, monthly sediment-trap data from Lake Sihailongwan in north-eastern China were used for elucidation of varve formation and for alkenone calibration against measured water

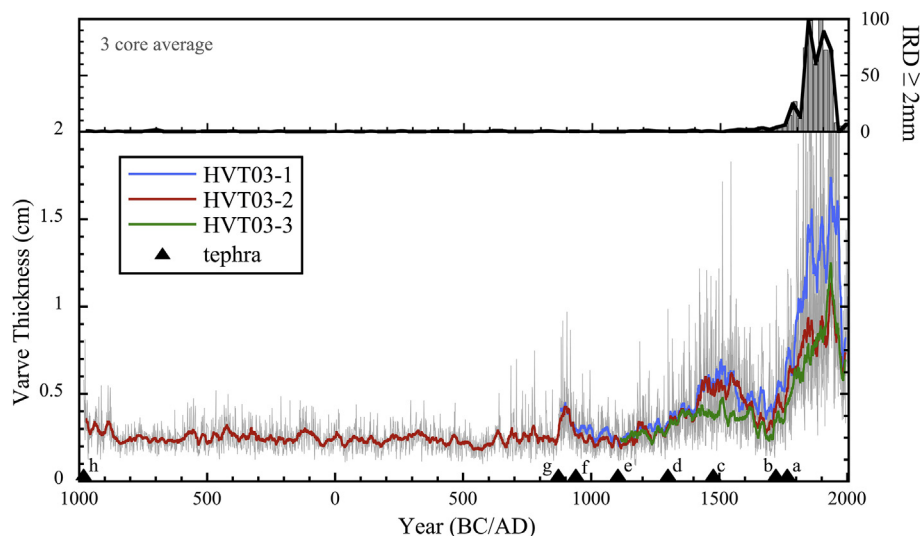


Fig. 33. Combined records of varve thickness and ice-rafted debris (IRD ≥ 2 mm size fractions shown as the average from the three coring sites HVT03-1, HVT03-2 and HVT03-3) in the Lake Hvítárvatn sequence in Iceland for the last 3000 years. Bold lines indicate varve thickness with 20-year running averages superimposed on annual data shown in grey. IRD was counted in consecutive 20-year intervals. Grey bars represent the number of clasts per 20 years, while the bold line represents a smoothed cubic spline. Positions of tephra layers 'a' to 'h' were used to anchor the varve chronology (modified after Larsen et al., 2011).

temperatures. Hardly any alkenone-producing haptophyte algae were present during the ice-covered winter period because heavy snow limits light penetration (Chu et al., 2005a). Alkenone-based temperature reconstructions should therefore represent water temperatures during ice-free summer growing seasons. The reconstructed summer temperature record of the past 1600 years for Lake Sihailongwan documents four cold periods of AD 480–860, 1260–1300, 1510–1570 and 1800–1900 (Chu et al., 2012) that compare well with seasonal temperature anomalies reported in historical documents during the same time periods. Such an approach is only possible in China where historical documents reach far back in time. The “Annals of the Choson Dynasty” (AD 1392–1910) with daily climatic information in more than 1800 volumes has developed into an invaluable documentary source for critical ground truthing of regional palaeoclimatic reconstructions.

6.5.2.5. Wind. Wind is rarely documented in sediment records. One unusual occasion is the varved record of Meerfelder Maar in Germany (Martin-Puertas et al., 2012) where 2760 cal BP marks the onset of about two centuries of varves with doubled thickness coinciding with the Homeric solar minimum (Fig. 27). This increased varve thickness resulted from stronger winds after ice break-up in spring and upwelling of nutrients from the hypolimnion as well as from increased wave activity along the shore acting as an erosive agent (Martin-Puertas et al., 2012).

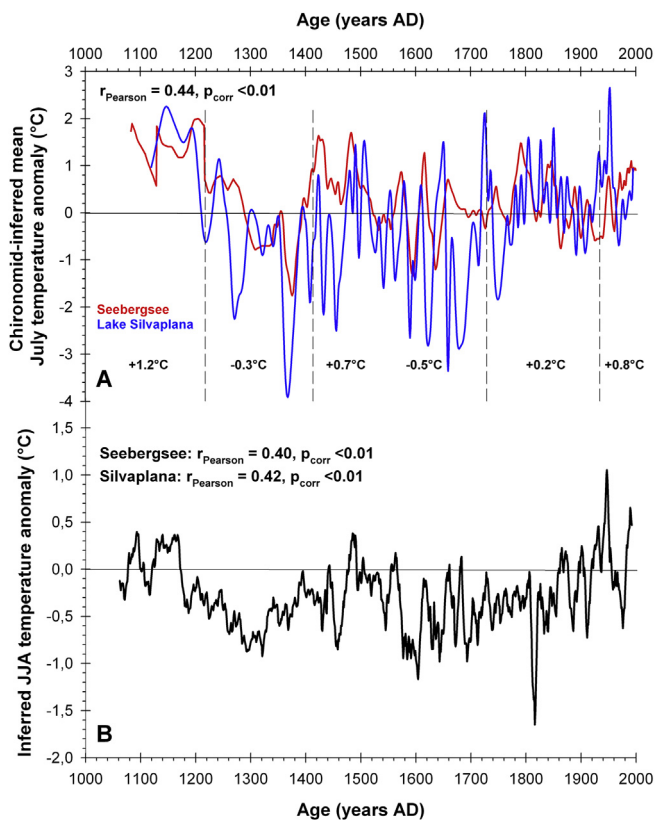


Fig. 34. (A) Chironomid-inferred July mean temperature anomalies from Swiss lakes Seebensee (red line) and Silvaplana (blue line). Numbers are average temperature anomalies compared to average temperatures of 11.3 °C for 1961–1990. (B) Composite June–July–August (JJA) temperature reconstructions based on six tree-ring records and the biogenic silica record from varved Lake Silvaplana (Trachsel et al., 2012). The Pearson correlation coefficient (r_{Pearson}) between the two chironomid-based reconstructions refers to Larocque-Tobler et al. (2012) and to a multi-archive reconstruction by Trachsel et al. (2012).

Another example concerns the varve record from Lower Mystic Lake in the USA (Besonen et al., 2008). Annual laminations are interspersed by several anomalous graded beds during the last millennium. Historic data support the interpretation that 10 of these event layers correspond to hurricanes of category 2–3 that made available large amounts of minerogenic matter from the catchment and the flooded shoreline. Transport was facilitated by simultaneous heavy rainfall.

7. Outlook

Annually laminated sediment records provide accurate time control for a multitude of palaeoenvironmentally relevant sedimentary parameters and document the frequency and rates of annual to millennial-scale climatic oscillations. Monitoring approaches such as sediment trapping provide detailed characterisation of modern sedimentary processes that can be applied to interpret these records and enhance the reliability of mechanistic models of varve formation. Furthermore, their accurate chronology makes them suitable for an emerging transformative concept: “forward modelling” or modelling of the climate indicators contained in natural archives (Braconnot et al., 2012). The increasing availability of modern instrumental environmental and meteorological time-series can aid in rigorous calibrations of palaeoenvironmental proxies in local varve settings, assessment of statistical error margins, and enhancing the validity of interpretations. Moreover, varve records lend themselves to high-resolution and continuous non-destructive sediment logging-techniques and thus economically provide a wealth of annual to seasonal information. In combination with process studies, such detailed information will be able to provide feedback and ground truthing for climate models.

Ongoing climate studies focus on three major research questions (Kamenik et al., 2009): (1) characterising and quantifying natural climate variability, (2) understanding and quantifying the anthropogenic forcing component of natural climatic processes, and (3) estimating ecological, economic, social and political risks resulting from the combined effects of (1) and (2) on future climate. Improved comprehension of past climatic changes is an incontrovertible axiom – a necessity – to understand future climatic change and can be achieved for the past few decades by instrumental data that only rarely reach back to the late 19th century. Assessments on longer time scales must typically be based on the interpretation of natural archives, such as lacustrine sediments that can provide excellent records of palaeoenvironmental conditions with seasonal to annual temporal resolution in regions with human habitation. These records are compatible with mounting evidence of abrupt and periodic climate change on various timescales during the Holocene and illustrate the dynamic nature of our climate system.

Rapid reactions of local hydrological systems to environmental change coupled with high sedimentation rates facilitate high-resolution studies that can potentially employ a wide range of sedimentological, geochemical, physical and biological methods. Due to the exceptionally high temporal resolution of annually laminated sediment sequences and combined with their accurate “internal” time scale in calendar years, varved sediments rank among the most precious natural environmental archives. Wise utilisation of varve records can provide a compass for the future, where global climate change with regional climate-related consequences will become one of the dominant factors controlling the well-being of humankind.

However, to combine and integrate records for obtaining best possible interpretations, lacustrine but also other sedimentary records from different regions need to be harmonised and

synchronised (Brauer et al., 2014). This task of integrating chronologies can only be successful if a robust chronological framework is developed for any individual record and as much uncertainties as possible are reduced. Therefore, Brauer et al. (2014) together with the authors of this paper regard harmonisation of chronologies for an improved integration of proxy time series as the major task for the coming years. For varve chronologies, like for other Quaternary dating tools, there are currently no accepted protocols of reporting the methodological approach or uncertainties and no common agreement on age reporting. The PAGES Varves Working Group will pick up this challenge and develop guidelines and protocols for varve chronologies as a first step towards such an integration of chronologies. Finally, we strongly support the recommendation of Brauer et al. (2014) that varve chronologists should be included from the beginning of any project related to annually laminated sediments in order to develop the best dating and sampling strategies which are the key for sound interpretations.

With the words of Paddy O'Sullivan, the main aim of this article is to compile recent developments in the field of varve studies, in the hope that the advantages of annually laminated lake sediments may become appreciated by a wider audience of students and young scientists involved with late Quaternary climatic and environmental processes (O'Sullivan, 1983).

Recommended reading

For further reading we particularly suggest interdisciplinary and multiproxy case studies on varved lake records from Elk Lake, USA (Bradbury et al., 1993), from Baldeggersee, Switzerland (Wehrli et al., 1997) and from Lake Gościąg, Poland (Ralska-Jasiewiczowa et al., 1998). Additional compilations of topical papers have been published as proceedings of dedicated conferences and workshops (Schlüchter, 1979; Saarnisto and Kahra, 1992; Hicks et al., 1994; Kemp, 1996; Francus et al., 2013b).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.quascirev.2015.03.019>.

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