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Invited review

Varves in lake sediments – a review

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A B S T R A C T

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.

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

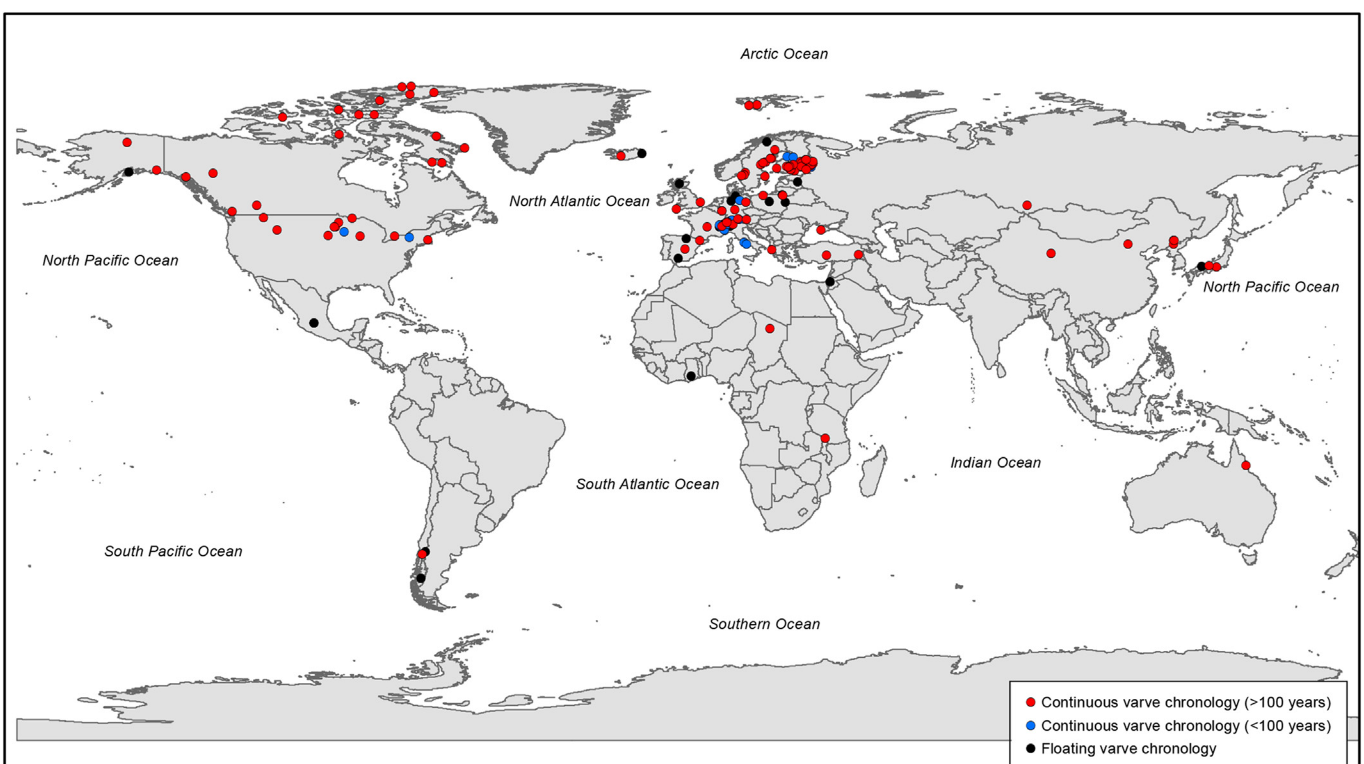

Fig. 1. Worldwide distribution of 143 published and peer-reviewed lacustrine varved Holocene and Pleistocene sediment records (cf. e-component 2, Supplementary data). Note that many varved sites are not shown if they are unpublished or incompletely described in terms of varve chronology or varve model and components.