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Tracking the impact of mid- to late Holocene climate change and anthropogenic activities on Lake Holzmaar using an updated Holocene chronology

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ABSTRACT

The mid- to late Holocene interval is characterised by a highly variable climate in response to a gradual change in orbital insolation. The seasonal impact of these changes on the Eifel Maar region is not yet well documented largely due to uncertainties about the completeness of this archive ("missing varves" in the well known Lake Holzmaar) and a limited understanding of the factors (e.g. temperature, precipitation) influencing the seasonality archived within the lamination/varves. In this study we approach these challenges from a different perspective. Using detailed microfacies investigations we: (1) demonstrate that the ambiguity about the "missing varves" is related to the climate induced complex biotic and abiotic laminations that led to mis-identification of varves; (2) use a combination of detailed microfacies investigations (varve structure, seasonality of biotic and abiotic signals), lamination quality, varve counts on multiple cores, published and new radiocarbon dates to develop a continuous master chronology based on the Bayesian modelling approach. The dates of major climate, volcanic, and archaeological event(s) determined using our model are in good agreement with the independently determined ages of the same events from other archives, confirming the accuracy of our age model; (3) test the sensitivity of the seasonal proxies to the available data on mid-Holocene changes in temperature and precipitation; (4) demonstrate that the changes in lake eutrophicity are correlative with temperature changes in NW Europe and probably triggered by solar variability; and (5) show that the early Iron Age onset of eutrophication in Lake Holzmaar was climate induced and began several decades before the impact of anthropogenic activity was seen in the form of intensified detrital erosion in the catchment area. Our work has implications for understanding the impact of climate change and anthropogenic activities on limnological systems.

1. Introduction

Recent studies have provided new information on the regional differences, seasonality, and duration of response to extreme climate events (Alley and Ágústsdóttir, 2005; Berger and Guilaine, 2009; Prasad et al., 2009a; Magny et al., 2011; Swierczynski et al., 2013; Corella et al., 2014; Feurdean et al., 2014; Shuman et al., 2014) highlighting the importance of well dated high resolution climate archives in obtaining "snap shots" of regional impact of global climate change. A crucial prerequisite for such reconstructions is an understanding of the link between climate parameters (e.g. temperature, precipitation) and the proxies preserved within the archives. Monitoring, in combination with investigations on recent varves, has been used to establish the link between limnological processes and proxies (e.g. Zahrer et al., 2013). Recent attempts to explore the long term stability of such links have focussed on geochemical data (Si/Ti) and varve thickness as indicators of wind stress (Martin-Puertas et al., 2012a, 2012b). However, far more detailed information on climate and proxy links can potentially be obtained by microfacies investigations on seasonal laminae comprising ecologically sensitive biota. Such information is especially crucial for the mid- to late Holocene period when climate records exhibit high variability in response to the gradual change in orbital insolation (Magny, 1993; Magny et al., 2012; Roberts et al., 2012; Morley et al., 2014). The impact of these climate changes on the regional ecosystem is not yet well documented, partly due to the challenges associated with disentangling the anthropogenic and the climate impacts. In such a scenario, seasonally laminated varved lake sediments from the Eifel Maar region are a valuable archive as the preserved biotic and abiotic signals have the potential of providing detailed information on the impact of climate change and anthropogenic activities on the ecosystem (Zolitschka, 1998; Kattel and Sirocko, 2011; Herbig and Sirocko, 2013). While the early and late Holocene sediments from the Lake Holzmaar have been explored in seasonal resolution, the same level of detail is lacking for the mid- to late Holocene interval largely due to uncertainties about the chronology, ambiguity about the nature

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of laminations (missing varves?) and the reasons thereof, and a limited understanding of the factors (e.g. temperature, precipitation) influencing the seasonality archived within the lamination/varves.

Most of the Eifel Maar lakes are closed basins with bottom anoxia that resulted in the formation and preservation of high resolution, largely varved lake sediments (e.g. Hajdas et al., 1995; Brauer et al., 2000; Sirocko et al., 2013). Seasonal scale geochemical, microfacies, and biological signatures in these sediments provide evidence of sensitivity to past climate change (Brüchmann, 1998; Brathauer et al., 1999; Zolitschka et al., 2000; Prasad et al., 2006, 2009b; Kattel and Sirocko, 2011) and anthropogenic activities (Kienel et al., 2005; Martin-Puertas et al., 2012a, 2012b; Musa Bandowe et al., 2014).

In this study we focus on the Lake Holzmaar from the Eifel Maar region. The lake is dimictic and holomictic and summer anoxic conditions exist below a water depth of 15 m (Scharf and Oehms, 1992). The planktonic diatom assemblages and chrysophytes preserved in the lake sediments are sensitive to seasonal changes in nutrient (Si, P) ratios, eutrophic status, and varying lake circulation patterns (see references in Baier et al., 2004b; Kienel et al., 2013). A prerequisite for our study is an accurate chronology as it offers the possibility of establishing a link between archived proxies and independently dated natural and anthropogenic forcings. However, the upper part of the Holzmaar cores encompassing mid- to late Holocene are not clearly laminated — there is a discrepancy between radiocarbon dating and varve counting (Hajdas et al., 1995; Zolitschka, 1998; Zolitschka et al., 2000; Prasad et al., 2006, 2009b; Sirocko et al., 2013) that could potentially cast doubt on the wider regional significance of any investigation on this core section. Therefore, we have undertaken a comprehensive approach that involved: (1) investigating the structure and quality of laminations to identify and count the varved sections in multiple cores; (2) compiling new (this study) and previously available Holocene varve counting data from five Holzmaar cores to develop a master chronology using Bayesian age modelling; and (3) tested the link between the reconstructed mid-Holocene limnology and independently reconstructed regional temperature and precipitation. Based on the outcome of (2) and (3), we evaluate the impact of climate change and anthropogenic activities on the lacustrine system during the Iron Age.

Uncalibrated ^{14}C dates are given as "^{14}C a", calibrated ^{14}C ages are given as "cal a". Absolute archaeological date is presented as BC. The age of the well known 8.2 ka event determined from the ice cores is reported relative to AD 2000 as b2k.

2. Previous work on Lake Holzmaar

2.1. Core sediments, lithology, and previous studies on mid- to late Holocene sediments

Sediment cores (HZM-B/C and HZM-1/2/3) were recovered from Lake Holzmaar with a modified Livingstone Piston-Corer during the summers of 1984, 1990 and 1992 (Fig. 1A). A continuous sediment record was developed by overlapping 2 m sections of several parallel cores. Two additional overlapping sediment cores (HZM-4a, HZM-4b) were raised from the centre of the lake in 1996 using a Usinger system (Mingram et al., 2005).

The composite lithology (Zolitschka, 1998) is shown in Fig. 1B. The cores largely comprise diatom rich laminated sediments and show the presence of two tephra layers — the Ulmener Maar Tephra (UMT) and the Laacher See Tephra (LST) (Zolitschka, 1998). Rein (1996) identified over 1000 micro-marker layers (henceforth referred to as HMM) and

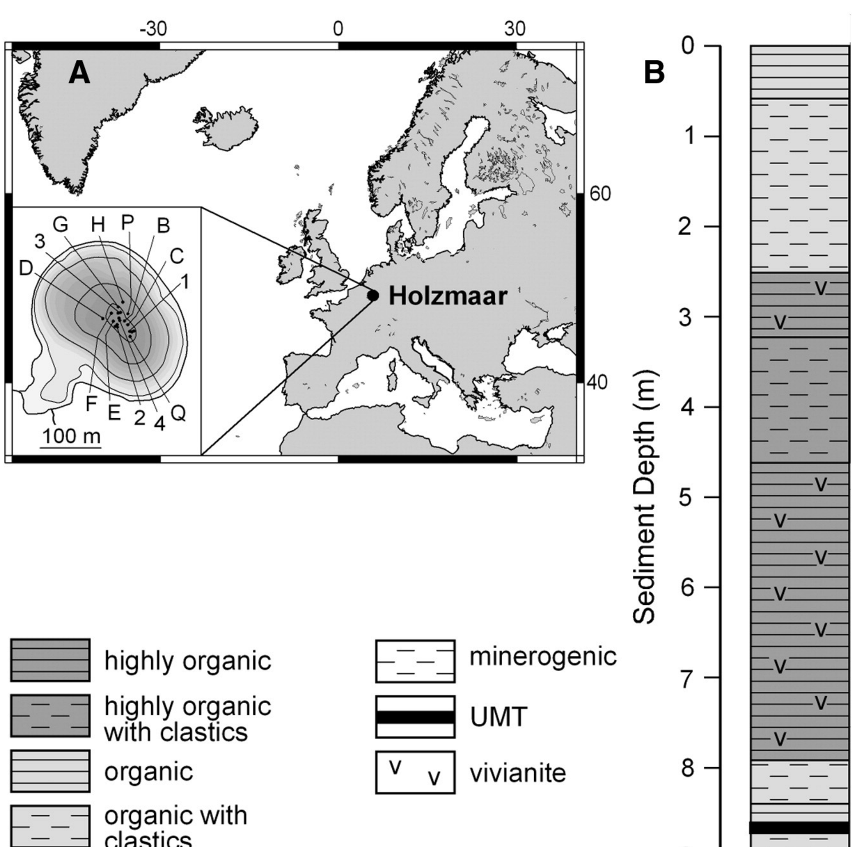

Fig. 1. (A) Location of the study area and HZM cores. Inset shows the position of different cores raised from this lake. (B) Holzmaar core lithology (modified from Zolitschka (1998).