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Late Neolithic Mondsee Culture in Austria: living on lakes and living with flood risk?

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Abstract

Neolithic and Bronze Age lake-dwellings in the European Alps became recently protected under the UNESCO World Heritage. However, only little is known about the cultural history of the related pre-historic communities, their adaptation strategies to environmental changes and particularly about the almost synchronous decline of many of these settlements around the transition from the Late Neolithic to the Early Bronze Age. For example, there is an ongoing debate whether the abandonment of Late Neolithic lake-dwellings at Lake Mondsee (Upper Austria) was caused by unfavourable climate conditions or a single catastrophic event. Within the varved sediments of Lake Mondsee we investigated the occurrence of intercalated detrital layers from major floods and debris flows to unravel extreme surface runoff recurrence during the Neolithic settlement phase. A combination of detailed sediment microfacies analysis and µXRF element scanning allows distinguishing debris flow and flood deposits. A total of 60 flood and 12 debris flow event layers was detected between 4000 and 7000 varve yr BP. Compared to the centennial- to millennial-scale average, a period of increased runoff event frequency can be identified between 4450 and 5900 varve yr BP. Enhanced flood frequency is accompanied by predominantly siliciclastic sediment supply between 5000 and 5500 varve yr BP and enhanced dolomitic sediment supply between 4500 and 5000 varve yr BP, revealing a change from regional floods to more local runoff events. Interestingly, during the interval of highest flood frequency a change in the location and the construction technique of the Neolithic lake-dwellings at Lake Mondsee can be observed. While lake-dwellings of the first settlement phase (ca. 5750–5200 cal. yr BP) were constructed on wetlands, later constructions (ca. 5400–4650 cal. yr BP) were built on piles upon the water, possibly indicating an adaptation to either increased flood risk or a general increase of the lake-level. However, also other than climatic factors (e.g. socio-economic changes) must have influenced the decline of the Mondsee Culture because flood activity generally decreased since 4450 varve yr BP, but no new lake-dwellings have been established thereafter.

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1 Introduction

The catastrophic impact of past climatic changes on pre-historic societies has been the topic of several studies during the last decade (e.g. Haug et al., 2003; Webster et al., 2007; Yancheva et al., 2007; Staubwasser et al., 2003; deMenocal, 2001). However, the demise of ancient civilizations might be more likely driven by a complex interplay of changing environmental conditions and several other factors such as socio-economic changes or natural disasters (e.g. Magny, 2004; Fedele et al., 2008) with distinguishing between these not always being straightforward. Unfavourable climate conditions have also been proposed to be the main cause for the large-scale and broadly synchronous abandonment of lake-dwellings in the Alpine region at the transition between the Neolithic and the Bronze Age (Magny, 1993, 2004). For example, there is indication that climatic changes might have been responsible for the decline of the Late Neolithic Mondsee Culture of Upper Austria (Schmidt, 1986; Offenberger, 1986). However, also a catastrophic landslide event has been proposed to have caused the disappearance of lake-dwellings at this site (Janik, 1969; Schulz, 2008). Hence, further studies are necessary to unravel the local factors leading to the abandonment of Neolithic settlements at Lake Mondsee. This might also provide valuable information about the impact of climate variability on Neolithic lake-shore settlements on a larger spatial scale. In the particular case of the Alpine lake-dwellings, a cold reversal, reflected by rising lake-levels (Magny and Haas, 2004; Magny, 2004) and glacier advances (Ivy-Ochs et al., 2009), between 5600 and 5300 cal. yr BP has been identified, which probably affected Neolithic cultures in the circum-Alpine region. This indicates a significant and overall influence of climate change on pre-historic settlements. However, limitations in the temporal resolution and chronological precision of different geoarchives still represent a major obstacle in investigating the influence of climate change and short-term hydro-meteorological events on early human societies and their settlements. Within this context, annually laminated lake sediments, which are characterized by a robust age control and record climatic changes directly in the habitat of the pre-historic lake-dwellers, can provide valuable information about past environmental conditions (e.g. hydrological changes) and their influence on the settlements.

The varved sediments of Lake Mondsee (Upper Austria) represent an ideal archive of past climate history and changing environmental conditions (e.g. Lauterbach et al., 2011; Klee and Schmidt, 1987; Schultze and Niederreiter, 1990; Schmidt, 1991), but also historical flood events (Swierczynski et al., 2012). The present study of Lake Mondsee sediments focuses on flood and debris flow event layer deposition between 7000 and 4000 varve yr BP, providing information about hydrological changes within this interval at high temporal resolution. The established unique event chronology enables, in comparison with ^{14}C dates from three Neolithic lake-dwelling sites around the lake (Felber, 1970, 1974, 1975, 1985; Felber and Pak, 1973; Schmidt, 1986), the evaluation of possible impacts of changes in runoff activity on the decline of Neolithic lake-dwellings at Lake Mondsee and the hypothesis of increased lake-levels at the end of the Neolithic.

2 Study area

Lake Mondsee is located at the northeastern fringe of the European Alps (Upper Austria, 47° 49′ N, 13° 24′ E, 481 m a.s.l.), about 40 km east of Salzburg (Fig. 1). The lake has a surface area of about 14 km^2 and a maximum depth of 68 m. The lake basin can be divided into a shallower northern and a deeper southern part. Three main rivers (Griesler Ache/Fuschler Ache, Zeller Ache and Wangauer Ache) feed the northern lake basin, whereas only several smaller streams discharge into the southern basin. The only outlet (Seeache) is located at the southern end of Lake Mondsee and drains into Lake Attersee. A Tertiary thrust fault, tracking along the southern lake shoreline, divides the catchment ($\sim$ 247 km^2) into a southern and a northern part with two different, clearly distinguishable geological units (Fig. 1). Rhenodanubic Flysch sediments and Last Glacial moraines characterize the gentle hills around the northern lake basin, whereas the southern shoreline of the lake is defined by the steep-sloping mountains of

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the Northern Calcareous Alps, composed of the Triassic Main Dolomite and Mesozoic limestones.

The climate of the Lake Mondsee region, being influenced by Atlantic and Mediterranean air masses (Sodemann and Zubler, 2010), is characterized by warm summers and frequent precipitation (annual average ~ 1550 mm for the period 1971–2000, Central Institute for Meteorology and Geodynamics (ZAMG), Vienna, Austria). As typical for the NE Alps, the precipitation maximum and in consequence extreme floods occur in July and August (Parajka et al., 2010). As indicated by historical records of daily lake water level for the last 100 yr, only very few flood events occur in winter (e.g. 1974) and autumn (e.g. 1899, 1920) (Swierczynski et al., 2009).

3 Neolithic lake-dwellings at Lake Mondsee

First research on Alpine lake-dwellings, since 2011 protected under the UNESCO World Heritage, was already published in the mid-19th century (Keller, 1854), reporting the finding of a submerged Bronze Age settlement in Lake Zurich. Within the following decades, several other Neolithic and Bronze Age settlements along Alpine lakes were discovered, accompanied by a lively debate about construction techniques and the socio-cultural and environmental conditions during the settlement phase (see Menotti, 2001, 2004, 2009, for a review).

Three lake-dwelling sites have so far been discovered along the shorelines of the southern basin of Lake Mondsee in the Salzkammergut lake district (Fig. 1). Radiocarbon dates obtained from several wooden artefacts from these lake-dwellings clearly indicate a Young to Final Neolithic age (Felber, 1970, 1974, 1975, 1985; Felber and Pak, 1973; Ruttkay et al., 2004). The site "See", which has already been described in the second half of the 19th century (Much, 1872, 1874, 1876) and after whose artefacts the Neolithic Mondsee Culture has been named, is located close to the lake outlet Seeache. Sedimentological and pollen analyses of a sediment core from the lake outlet (Schmidt, 1986) indicate the presence of landuse indicators in a cultural horizon, which is palynologically dated to the Younger Atlantic. This cultural horizon, which has been interpreted as reworked/washed-away material from prehistoric houses, is underlain by clastic material, which is thought to reflect a transgressive phase with increased lake-levels and has been dated to 4720 ± 100 ^{14}C yr BP (5055–5661 cal. yr BP, Schmidt, 1986). This age is in good agreement with conventional radiocarbon dates obtained from wooden artefacts from the Neolithic lake-dwellings at site "See", dating between 4660 ± 80 and 4910 ± 130 ^{14}C yr BP (5062–5589 and 5325–5920 cal. yr BP, Table 1, Felber, 1970, 1985). The two other lake-dwelling sites "Scharfling" and "Mooswinkel" are located at the southern and northern shoreline of the lake, respectively. While remnants from the site "Scharfling", which is located ca. 3.5 km west of the site "See", are dated to the almost similar time interval as those from site "See", namely between 4660 ± 90 and 4940 ± 120 ^{14}C yr BP (5054–5590 and 5331–5931 cal. yr BP, Table 1, Felber, 1974), the site "Mooswinkel" on the northern shore is apparently slightly younger, dating between 4260 ± 90 and 4560 ± 100 ^{14}C yr BP (4525–5213 and 4883–5576 cal. yr BP, Table 1, Felber, 1975; Felber and Pak, 1973).

Interestingly, while archaeological and palaeobotanical studies have proven the existence of lake-dwellings until the Early and Middle Bronze Age at other lakes in the European Alps (e.g. Magny, 1993; Billaud and Marguet, 2005; Pétrequin et al., 2005; de Marinis et al., 2005; Magny et al., 2009; Menotti, 2004), no lake-dwellings younger than the Neolithic have been discovered at Lake Mondsee so far (Ruttkay et al., 2004). This observation is in general agreement with the widely observed Late Neolithic decline of lake-dwellings in the Alpine region, for which a climate deterioration towards wetter conditions, probably aggravated by socio-economic changes, has been proposed to be the cause (Magny, 2004; Menotti, 2009). However, an attention-grabbing article in a popular magazine recently suggested a single catastrophic rock fall event and a subsequent tsunami as a likely cause for the abrupt abandonment of the lake-dwellings at Lake Mondsee (Schulz, 2008). Although this hypothesis can be clearly rejected from an archaeological perspective (Offenberger, 2012; Breitwieser, 2010), previous investigations on the morphology of the lake and the catchment close to the outlet provided

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indeed evidence for landslide deposits in the riverbed connecting Lake Mondsee and Lake Attersee (Janik, 1969). Nevertheless, the exact timing of these deposits and particularly the proposed connection to the abandonment of the Neolithic lake-dwellings are highly questionable. Hence, further investigations are necessary to unravel the possible influences of climate conditions but also other factors on the decline of the Neolithic Mondsee Culture.

4 Methods

4.1 Fieldwork

Two overlapping piston cores and three short gravity cores were retrieved from the southern basin of Lake Mondsee (coring site at 47° 48′ 41″ N, 13° 24′ 09″ E, 62 m water depth; Fig. 1) in June 2005 by using UWITEC coring devices. All cores were subsequently opened, photographed and lithostratigraphically described on-site in a specially installed field lab. The 2-m-long segments of the two piston cores and the gravity cores were then visually correlated by using distinct lithological marker layers, resulting in a ca. 15 m long continuous composite profile, which covers the complete Holocene and Lateglacial sedimentation history of Lake Mondsee (for further details see Lauterbach et al., 2011).

4.2 Sediment microfacies analysis and microscopic varve counting

A continuous set of large-scale petrographic thin sections was prepared from a series of overlapping sediment blocks (100 × 20 × 10 mm) taken from the sediment cores of the composite profile, following the method described by Brauer et al. (1999). Thin sections were examined for detailed sediment microfacies analysis under a ZEISS Axiophot polarisation microscope at 25–200× magnification. In addition, aiming at establishing a varve chronology for the Lake Mondsee sediments, continuous microscopic varve counting and thickness measurements were carried out in the distinctly laminated

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uppermost part of the Holocene sediment record (0–610 cm), whereas for the lowermost part (610–1129 cm) a varve-based sedimentation rate chronology was established. A detailed description of the microfacies of the Lake Mondsee sediments and the development of the Holocene varve chronology is given by Lauterbach et al. (2011). The present study focuses on the interval between 585 and 840 cm composite depth of the Lake Mondsee sediment record. Within this interval, intercalated detrital layers were counted and their thickness was measured. For testing statistical significances of detrital layer occurrence and a better visual comparison with other proxy records a Kernel regression with bandwidths of 30 and 500 yr (Swierczynski et al., 2012b; Mudelsee et al., 2003) was applied to the data set.

4.3 Radiocarbon dating and calibration

The varve counting-based chronology for the Holocene part of the Lake Mondsee sediment record was additionally controlled by ^{14}C dates. Therefore, terrestrial plant macrofossils (leaf fragments, seeds, bark) found in the sediments (Table 2) were dated by accelerator mass spectrometry (AMS) ^{14}C dating at the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research in Kiel. All conventional radiocarbon ages were calibrated using OxCal 4.1 (Ramsey, 1995, 2001, 2009) with the IntCal09 calibration data set (Reimer et al., 2009). In order to ensure comparability and to evaluate possible relationships between Neolithic settlement activities along the shores of Lake Mondsee and climatic events recorded in the sediment core, previously published conventional radiocarbon dates from archaeological findings from the three local lake-dwelling sites (Table 1, Felber, 1970, 1974, 1975, 1985; Felber and Pak, 1973) were carefully reviewed and also calibrated with OxCal 4.1 (Ramsey, 1995, 2001, 2009) using IntCal09 (Reimer et al., 2009). All calibrated ages are reported as 2σ probability ranges.

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4.4 Geochemical analyses

Semi-quantitative µXRF major element scanning was carried out at 200 µm resolution on impregnated sediment slabs from thin section preparation between 585 and 840 cm, using a vacuum-operating Eagle III XL micro X-ray fluorescence (µXRF) spectrometer with a low-power Rh X-ray tube at 40 kV and 300 mA (250 mm spot size, 60 s counting time, single scan line). Element intensities for Mg, Al and Ca are expressed as counts s^{-1} (cps), representing relative changes in element composition. The scanned sediment surfaces are identical to those prepared for thin sections, thus enabling a detailed comparison of high-resolution µXRF and microfacies data (Brauer et al., 2009).

5 Results

5.1 Chronology of the sediment record and dating of the Neolithic lake-dwellings

The chronology for the Holocene part of the Lake Mondsee sediment sequence and thus also the detrital layer record was established by combining microscopic varve counting (0–610 cm composite depth) and a varve counting-based sedimentation rate chronology (610–1129 cm composite depth (Fig. 2); for details see Lauterbach et al. (2011)). Estimating the accuracy of the varve chronology is possible by comparing independent varve counts for the sediments encompassing the last ca. 1600 yr carried out by two different examiners, which yields a maximum difference of ca. 50 yr, equivalent to a counting error of less than 3 % (Swierczynski et al., 2012b). Hence, an uncertainty range of ±50 yr (indicated in Fig. 2 by dashed lines) can also be considered as a reasonable error estimate for the varve chronology around the Neolithic settlement period. To further assess the reliability of the varve chronology, a supplementary age model based on AMS ^{14}C dates has been constructed. For this purpose, 12 radiocarbon dates obtained from terrestrial plant macrofossils from the interval between

550 and 950 cm composite depth were used (Table 2). The calibrated radiocarbon dates agree well with the varve chronology (Fig. 2), except one date (KIA32795), which was rejected for subsequent ^{14}C age modelling as the calibrated age is considerably younger than expected from the varve chronology. This is most probably owed to the very small sample size (Table 2), favouring contamination with modern carbon (Wohlfarth et al., 1998). In the following, the other 11 calibrated dates were used as input parameters for Bayesian age modelling with a *P_Sequence* deposition model (the model parameter *k* was set to 1) implemented in OxCal 4.1 (Ramsey, 2008). To avoid model inconsistencies such as unrealistically high uncertainty ranges at the upper and lower boundaries of the modelled interval, which usually occur when there are no radiocarbon dates, we chose a larger interval for ^{14}C-based age modelling (ca. 550–950 cm) than that actually under investigation (ca. 585–840 cm, ca. 4000–7000 varve yr BP). The agreement index A_{model} of 69.1 % for the resulting age-depth-model is fairly above the critical threshold of 60 %, proving the robustness of the model (Ramsey, 1995, 2001). The comparison of the varve- and radiocarbon-based age model reveals that both models are statistically indistinguishable within their uncertainty ranges in the interval under investigation, supporting the robustness of the original varve chronology, which is hence used as the chronological framework for the sediment-derived proxy data.

In order to evaluate the chronology of the Neolithic settlements at Lake Mondsee, we used 12 published conventional radiocarbon dates (Table 1, Felber, 1970, 1974, 1975, 1985; Felber and Pak, 1973), which were obtained from wooden artefacts from the three subaquatic lake-dwelling sites during previous archaeological surveys. In order to model the settlement phases of the three individual sites, the calibrated dates were used as input parameters for a *Phase* model implemented in OxCal 4.1 (Ramsey, 2009). As a result, the two settlements "Scharfling" and "See" on the southeastern and southern lake shore apparently existed almost contemporaneously (Fig. 3) from 5594 ± 167 to 5505 ± 111 cal. yr BP and from 5448 ± 134 to 5369 ± 147 cal. yr BP, respectively. In contrast, the site "Mooswinkel" appears to have been established slightly

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later (ca. 5167 ± 244 cal. yr BP) than the two other sites. The upper age boundary of the "Mooswinkel" settlement phase is dated to 5003 ± 351 cal. yr BP, a time when the two other sites apparently were already abandoned. Concerning the assessment of the reliability of the dating of the settlement phases, it should be mentioned that the wooden lake-dwellings from whose remnants the dated samples have been obtained likely existed not longer than a few decades after their construction (and the cutting of the trees, which is given by the radiocarbon age) and then were repaired or replaced by new buildings (Schlichtherle, 2004). Hence the radiocarbon dates are expected to reflect approximately also the time of the abandonment of a wooden construction within the dating uncertainty.

5.2 Sediment microfacies and geochemical properties

The Holocene sediments of Lake Mondsee are composed of varved calcite mud (Lauterbach et al., 2011; Schmidt, 1991) with frequently intercalated detrital layers. As revealed from µXRF data, the light sub-layers are enriched in Ca (Fig. 4) resulting from endogenic calcite precipitation after spring/summer algae bloom. In contrast, the dark sub-layers are enriched in siliciclastic elements (e.g. Ti), reflecting clastic sediment deposition during autumn/winter. Two types of detrital layers (type 1 and type 2) can be distinguished within the Lake Mondsee sediments (Swierczynski et al., 2012). Thick (0.9–32.0 mm) and mainly graded detrital layers reflect local debris flow events (detrital layer type 2). The enrichment of Mg, indicative for dolomitic rocks, and low contents of siliciclastic elements (e.g. Ti) reveal the Northern Calcareous Alps as the source region. In contrast, thin detrital layers (0.05–1.7 mm) are non-graded and composed of both, siliciclastic and dolomitic components (detrital layer type 1), thus revealing sediment delivery from both the northern and southern part of the catchment by regional-scale flood events. Thick detrital layers from flood events reveal a higher abundance and also increased thicknesses between 665 and 800 cm, whereas for debris flow-related layers no clear clustering can be observed. Increased Ti counts characterize the interval

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between 670 and 715 cm (4968–5497 varve yr BP), whereas Mg is enriched between 630 and 665 cm (4909–4482 varve yr BP) (Fig. 4).

5.3 Flood and debris flow deposition

By combining sediment microfacies and geochemical analyses, a total of 60 flood and 12 debris flow layers could be detected within the investigated interval between 585 and 840 cm composite depth (ca. 4000–7000 varve yr BP; Fig. 5). The mean recurrence of floods during this 3000 yr interval is ca. 67 yr, while debris flows have a mean recurrence interval of ca. 333 yr. Although anthropogenic land use is commonly regarded to influence erosion processes in the catchment, detrital layer deposition in Lake Mondsee has been shown to be mainly climate-controlled, even during recent times when human impact in the catchment was likely much more intense than during the Neolithic (Swierczynski et al., 2012).

On a multi-centennial to millennial time scale (kernel bandwidth of 500 yr), the flood activity is highest (mean flood recurrence of 40–50 yr) between ca. 5900 and 4450 varve yr BP compared to the whole interval under investigation (Fig. 5). By using a kernel bandwith of 30 yr, eight distinct episodes of increased flood frequency (FE 10 to FE 17; flood episodes FE 1 to FE 9 during the period younger than ca. 4000 varve yr BP are described in detail in Swierczynski et al., 2012a,b), each of ca. 50 yr duration and with flood recurrence rates of ~ 10 yr can be been identified in the Neolithic Lake Mondsee sediment record: FE 10 (4450–4500 varve yr BP), FE 11 (4650–4700 varve yr BP), FE 12 (4850–4900 varve yr BP), FE 13 (5050–5120 varve yr BP), FE 14 (5380–5420 varve yr BP), FE 15 (5800–5850 varve yr BP), FE 16 (6120–6170 varve yr BP) and FE 17 (6420–6470 varve yr BP). While floods have a recurrence of mainly > 30 yr prior to ca. 5900 varve yr BP, only interrupted by two major multi-decadal flood episodes (FE 16 and 17), flood activity clearly increased between 5900 and 4450 varve yr BP, revealing six distinct flood episodes (FE 10 to 15) with flood recurrence rates of 10–16 yr. Particularly the interval between ca. 5150 and 4500 varve yr BP is characterized by frequent flood episodes (four FE within ca. 650 yr)

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with high flood recurrence (< 10 yr). The period younger than 4450 varve yr BP shows, compared to the interval 5900–4450 varve yr BP, a relatively low flood activity with recurrence rates of 30 yr or more.

6 Discussion

According to phase modelling with OxCal 4.1 (Ramsey, 2009) for the available radiocarbon dates from the three archaeological sites at Lake Mondsee, two settling phases can be distinguished. The first settling phase (SP I; Fig. 3), incorporating the sites "Scharfling" and "See" at the southern and southeastern shores of Lake Mondsee, respectively, lasted from ca. 5750 to 5200 cal. yr BP, while the second settling phase (SP II), represented by the settlement "Mooswinkel" at the northern shore, lasted from ca. 5400 to 4650 cal. yr BP. In addition to these chronological and spatial disparities, also a diverging construction technique distinguishes the two settling phases. While the lake-dwellings of SP I were constructed on wetlands with the basement of the houses being probably only ca. 20–30 cm above the ground (Ruttkay, 2003), those of SP II were built on piles, likely indicative for buildings standing in the water (Offenberger, 1986, 2012; Ruttkay, 2003). In the following, the settlement history is compared with the observed decadal- to centennial-scale flood variability and regional-scale climatic changes.

Although climate in the Central Alps is generally regarded warmer and drier than today between ca. 10 500 and 3300 cal. yr BP (Ivy-Ochs et al., 2009), there is indication from pollen (Bortenschlager, 1970), tree-line (Nicolussi et al., 2005), lake-level (Magny, 2004) and glacier records (Ivy-Ochs et al., 2009; Holzhauser, 2007; Holzhauser et al., 2005) that this period was punctuated by several regional-scale climate deteriorations. In this context, the slight increase in flood variability at Lake Mondsee after ca. 6500 varve yr BP and particularly the more pronounced clustering of flood events after ca. 5900 varve yr BP are in good agreement with a phase of wetter and colder climate conditions in the Alps between 6300 and 5500 cal. yr BP, the Rotmoos I cold oscillation

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(Bortenschlager, 1970; Patzelt, 1977). Also the peaking flood activity in Lake Mondsee around 5100 varve yr BP is synchronous to a regional-scale cold/wet phase, the Rotmoos II oscillation (Bortenschlager, 1970; Patzelt, 1977), which lasted from ca. 5400 to 5000 cal. yr BP. This climate deterioration is also reflected by the burial of the Neolithic ice man from the Similaun by advancing glaciers, dated to ca. 5300–5050 cal. yr BP (Baroni and Orombelli, 1996; Bonani et al., 1994), revealing the regional significance of this short-term cold/wet event across the Alps. Increased precipitation and lake-level highstands due to climate deterioration during these intervals and possible consequences for Neolithic lake-dwellings have also been reported from other sites in Switzerland, Italy and France (Magny, 2004; Magny et al., 2006). Increased flood activity at Lake Mondsee between ca. 5900 and 4500 varve yr BP is furthermore in good correspondence with cold and wet climate conditions reported from the Austrian Central Alps for the periods between 5800 and 5400 cal. yr BP and around 5100 cal. yr BP (Schmidt et al., 2006, 2009). A drier episode around 5200 cal. yr BP in the Central Austrian Alps (Schmidt et al., 2009) is likely equivalent to the period of low flood recurrence in Lake Mondsee between FE 13 and 14.

Although an increase in flood frequency in the Lake Mondsee record is already visible after ca. 5900 varve yr BP, the first lake-dwellings of SP I were apparently established during a period of relatively low flood recurrence around 5750 cal. yr BP. Considering that flood-related lake-level changes of up to 2.5 m within a few days have been observed at Lake Mondsee during the last century (Swierczynski et al., 2009), the lake-dwellings "Scharfling" and "See", which were both constructed directly on the southern wetland plains, should be expected to be particularly vulnerable to increased flood risk after ca. 5900 varve yr BP. However, both lake-dwelling sites existed even during this interval, which culminated during FE 14 around 5400 varve yr BP (Fig. 6), and beyond. The abandonment of the SP I lake-dwellings (5505 ± 111 cal. yr BP at site "Scharfling", 5369 ± 147 cal. yr BP at site "See") apparently only occurred around 5200 cal. yr BP, during an interval of relatively low flood risk after FE 14. Hence, a causal relation between increased flood risk and both the change in the settlement location and the construction

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type cannot be definitely verified. In addition to flood risk, both settlements must also have been vulnerable to the effects of hydrologically triggered surface erosion processes, i.e. debris flows, after strong precipitation events as they were located close to the steep slopes of the Northern Calcareous Alps (maximum slope of 34 % in the Kienbach creek and cascades of up to 60 m close to the settlement "Scharfling"; personal communication Wildbach- und Lawinenverbauung), which are the source of local debris flows. Such erosion events are documented for recent times (Swierczynski et al., 2009) and also occurred during the Neolithic settlement period (Fig. 5), but since there is no significant clustering of debris flows around the time of the abandonment of the lake-dwellings at the southern shores of Lake Mondsee, a causal connection between both can be excluded. In summary, there is no clear indication that either increased flood risk or debris flow activity triggered the end of SP I at Lake Mondsee. However, evidence that hydrological changes other than floods or debris flows could have indeed influenced the end of SP I comes from a sediment core obtained close to the settlement "See". Abundant clastic Flysch material, deposited below the cultural horizon and dated to 5055–5661 cal. yr BP as well as erosion marks have been interpreted as indicators for a transgression phase and lake-level oscillations during the settlement phase (Schmidt, 1986). Probably the abandonment of the settlement "See" around 5369 ± 147 cal. yr BP was related to this transgression phase, as this site has been constructed on the flat wetland plain at the lake outlet, which experiences flooding when the lake-level increases. As highlighted by Schmidt (1986), the construction of the lake-dwellings indicates that they might have been able to sustain the normal annual lake-level oscillations and even small-scale floods but not a permanent lake-level increase of more than ca. 1 m.

Despite the evidence from several climate archives for significant climatic changes in the Alpine region during the second half of the fourth millennium BC and an apparently closely corresponding increase in flood risk at Lake Mondsee, the contemporaneous abandonment of the lake-dwelling sites "Scharfling" and "See", and the subsequent shift of Neolithic settlement activity to the northern shore of Lake Mondsee is not necessarily attributable solely to climatic changes. Although the onset of the second settling phase (SP II) at the site “Mooswinkel” falls within an interval of increased flood activity, incorporating the prominent flood episodes FE 11, 12 and 13, and the shift in the location as well as the construction of the “Mooswinkel” buildings on piles upon the water might hence be interpreted as a possible adaptation to increased flood risk or lake-levels, archaeological investigations indicate that these lake-dwellings might have rather been constructed for a special purpose (a ferry landing, Ruttkay et al., 2004) than being a consequence of increased flood risk. Furthermore, geochemical analyses on the Lake Mondsee sediments indicate a change from predominantly siliciclastic sediment supply, reflecting rather regional scale flooding, to enhanced dolomitic sediment supply, reflecting more frequent local runoff events from the Northern Calcareous Alps (close to the SP I settlements) only at about 5000 varve yr BP and thus clearly after the abandonment of the lake-dwelling sites “Scharfling” and “See” at the southern shores. This indicates that changing/increasing flood risk might have played a role in the changed settlement strategy of the Mondsee Culture but was certainly not the only cause. Other possible influences might have been socio-cultural changes (Magny, 2004) or a climate-induced general lake-level increase, which has been proposed from sedimentological observations close to the site “See” (Schmidt, 1986) but is also seen in other Alpine lake records (Magny, 2004; Magny et al., 2006) during the respective interval between ca. 5650 and 5200 cal. yr BP. However, this remains speculative and further research is necessary to clarify this.

Concerning the final abandonment of lake-dwellings at Lake Mondsee and the decline of the Mondsee Culture, equivalent to the end of SP II at the site “Mooswinkel” around 4650 cal. yr BP, increased flood risk was most likely not the main trigger as flood frequency was already high during the establishment of this settlement and the shift to more regional-scale floods around 5000 varve yr BP with frequent input of siliciclastic material from the Flysch hills must have affected also this site. Moreover, there is no indication for a re-appearance of lake-shore settlements after ca. 4450 varve yr BP, when flood risk in the Lake Mondsee region decreased. Hence, changes in flood risk might

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have influenced the Late Neolithic communities at Lake Mondsee to a certain degree but clearly did not cause the decline of the whole culture. More likely a complex interplay of climatic and socio-cultural changes (Magny, 2004) and/or a change in the subsistence strategy (Menotti, 2003, 2009), e.g. hinterland migration or the beginning of alpine pasturing during the Late Neolithic (Bortenschlager and Oeggl, 2000), caused the abandonment of the lake-dwellings.

Besides the possible climatic influence, also a single catastrophic rockfall event has been proposed to have caused the abrupt abandonment of the lake-dwellings, at least at the southern shores of Lake Mondsee (Schulz, 2008). However, in contrast to the hypothesis of increased flood risk or a rising lake-level, which cannot be absolutely excluded, such a catastrophic event can be clearly rejected as the cause for the decline of the Neolithic Mondsee Culture from archaeological (Offenberger, 2012; Breitwieser, 2010) and sedimentological evidence. Within the whole investigated sediment sequence, there is no indication for a prominent event layer other than the normal mm- to cm-scale flood and debris flow layers that might be related to a large rockfall/landslide event. Such an event must have supplied large amounts of suspended detrital material into the lake and thus should be reflected by a turbiditic event layer of outstanding thickness in the sediment record as shown for earthquake-related (Lauterbach et al., 2012; Fanetti et al., 2008; Chapron et al., 1999) or gravitationally triggered mass wasting deposits (Girardclos et al., 2007; Schnellmann et al., 2005), but there is none such layer or indication for mass movements, rock falls or a hiatus in the entire lake sediment record. Hence, a single exceptional flood, debris flow or rock fall event can be rejected as the cause for the decline of the Neolithic Mondsee Culture.

7 Conclusions

We investigated the recurrence of extreme hydro-meteorological events (local debris flows and regional floods) in the sediment record of Lake Mondsee (Upper Austria) during the interval of Neolithic settlement activity between 4000 and 7000 varve yr BP.

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Increased abundance of flood events characterizes the interval between ca. 5900 and 4450 varve yr, which further features a significant change in the Neolithic settlement strategy from lakedwellings built on the wetlands at the southern and southeastern shores of Lake Mondsee (5750–5200 cal. yr BP) to lakedwellings built on piles upon the water at the northern lake shore (5400–4650 cal. yr BP). The observed changes in settlement strategy at Lake Mondsee correspond to a general and most probably climate-related decline of Neolithic settlements in the Alpine region between 5650 and 5200 cal. yr BP. Increased flood risk at Lake Mondsee during this interval is in agreement with highly variable lakelevels and also glacier advances during the Rotmoos cold oscillations, indicating colder and wetter climate conditions in the Alpine region. However, although the Lake Mondsee sediment record shows evidence of enhanced flood risk during the Neolithic, this is unlikely to be the only cause for the change in settlement strategy around 5300 cal. yr BP. More likely a combination of several factors, including increased flood recurrence, a rising lake-level but probably also socio-economic changes was responsible for the observed shift in human activity. Also the final decline of the Mondsee Culture around 4650 cal. yr BP cannot be related solely to climatic changes because flood risk decreased after ca. 4500 varve yr BP but no new settlements were established thereafter. In order to better understand the effects of climate variability on pre-historic lake-dweller societies, more highly resolved lake sediment records, which consider regional and seasonal peculiarities of climate development as well as more interdisciplinary research between archaeologists and palaeoclimatologists are needed.

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Table 1. Radiocarbon dates obtained from remnants of Neolithic lake-dwellings in Lake Mondsee. Conventional ^{14}C ages (Felber and Pak, 1973; Felber, 1974, 1975, 1970, 1985) were calibrated using OxCal 4.1 (Ramsey, 2001, 1995, 2009) with the IntCal09 calibration dataset (Reimer et al., 2009).

Sample	Location	Dated material	Conventional ^{14}C age (^{14}C yr BP $\pm\sigma$)	Calibrated age (cal. yr BP, 2σ range)
VRI-250	Mooswinkel	pile from lake-dwelling (probably *Populus*)	4560 ± 100	4883–5576
VRI-331	Mooswinkel	pile from lake-dwelling (*Picea abies*)	4350 ± 90	4657–5294
VRI-332	Mooswinkel	pile from lake-dwelling (*Picea abies*)	4260 ± 90	4525–5213
VRI-333	Mooswinkel	pile from lake-dwelling (*Picea abies*)	4430 ± 110	4826–5445
VRI-311	Scharfling	pile from lake-dwelling (*Picea abies*)	4940 ± 120	5331–5931
VRI-312	Scharfling	pile from lake-dwelling (*Acer pseudoplatanus*)	4870 ± 100	5326–5891
VRI-313	Scharfling	pile from lake-dwelling (*Fagus sylvatica*)	4660 ± 90	5054–5590
VRI-314	Scharfling	pile from lake-dwelling (*Picea abies*)	4780 ± 90	5312–5707
VRI-823	See	pile from lake-dwelling (undetermined)	4660 ± 80	5062–5589
VRI-37	See	pile from lake-dwelling (undetermined)	4910 ± 130	5325–5920
VRI-68	See	pile from lake-dwelling (undetermined)	4750 ± 90	5306–5653
VRI-119	See	pile from lake-dwelling (undetermined)	4800 ± 90	5319–5714

Table 2. Selected AMS ^{14}C dates obtained from terrestrial macrofossils from the Lake Mondsee sediment core. All conventional ^{14}C ages were calibrated using the OxCal 4.1 program (Ramsey, 1995, 2001, 2009) with the IntCal09 calibration data set (Reimer et al., 2009). Sample KIA32795 was rejected from age modelling with OxCal (for further explanations see the text). For a full account on radiocarbon dates from the Lake Mondsee sediment record and the primary varve-based age model see (Lauterbach et al., 2011).

Sample	Composite depth (cm)	Dated material	Carbon content (mg)/ $\delta^{13}C \pm \sigma$ (‰)	AMS ^{14}C age (yr BP $\pm \sigma$)	Calibrated age (cal. yr BP, 2σ range)
KIA36610	589.00	plant remains[b]	2.22/−27.03 ± 0.25	3618 ± 33	3839–4070
KIA36611	604.50	plant remains[b]	0.41/−29.03 ± 0.36	3697 ± 56	3880–4228
KIA29395	607.50	plant remains[b]	4.06/−29.21 ± 0.04	3848 ± 26	4155–4407
KIA39229	657.00	leaves[a]	1.61/−28.99 ± 0.09	4142 ± 31	4570–4824
KIA39230	685.00	leaves[a] & needle	2.28/−28.77 ± 0.12	4581 ± 34	5058–5447
KIA32793	708.75	twig & bark	4.89/−28.60 ± 0.05	4668 ± 28	5316–5566
KIA36612	732.25	wood & leaves	0.97/−27.69 ± 0.13	4883 ± 41	5488–5715
KIA32794	782.25	leaves[a]	1.04/−30.09 ± 0.15	5462 ± 36	6194–6310
KIA36619	818.75	plant remains[b]	1.65/−26.55 ± 0.13	5809 ± 36	6498–6717
KIA32795	873.00	plant remains[b]	0.28/−32.70 ± 0.23	6088 ± 104	6727–7246
KIA32796	916.50	leaves[a]	3.29/−29.61 ± 0.09	7129 ± 36	7869–8014
KIA39231	941.00	twig	0.95/−29.41 ± 0.12	7349 ± 48	8026–8311

[a] Undetermined terrestrial leaf fragments

[b] various undetermined terrestrial plant remains (leaves, wood, seeds)

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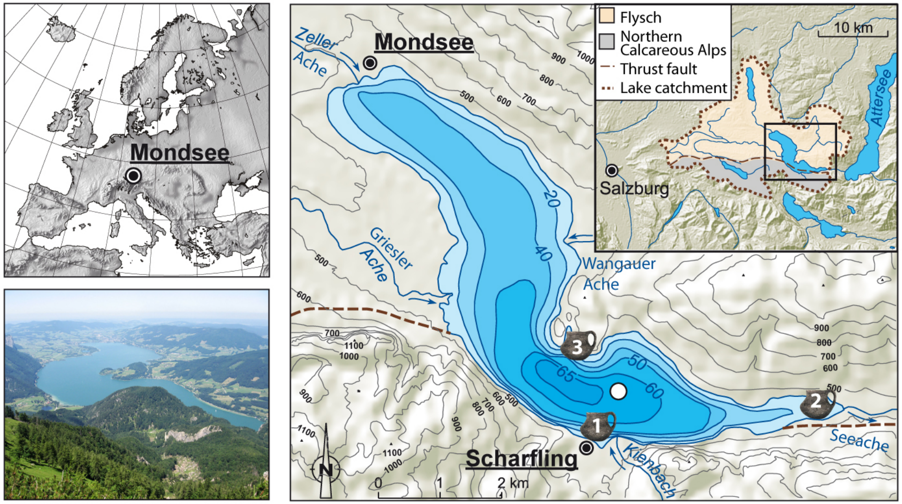

Fig. 1. Bathymetry of Lake Mondsee (depth below lake level), relief with isobaths and simplified geological map of the lake catchment. Three main rivers (Griesler Ache, Wangauer Ache and Zeller Ache) and the small creek Kienbach are the main sources of detrital input.

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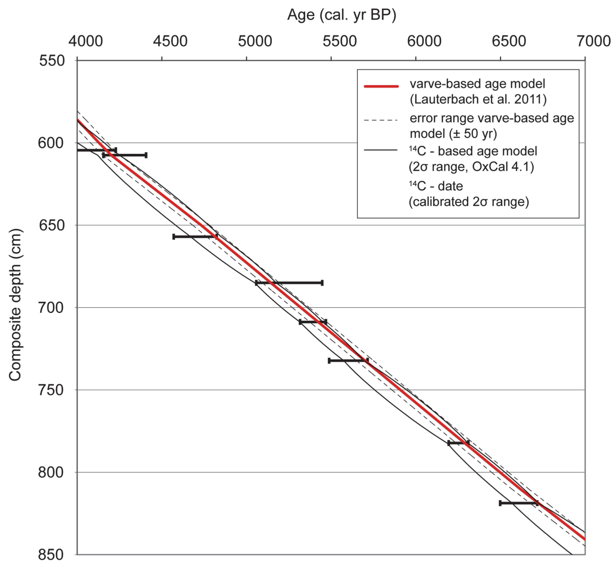

Fig. 2. Comparison of the primary varve-based age model (given with a counting uncertainty of ±50 yr as dashed lines) of the Lake Mondsee record (Lauterbach et al., 2011) and a secondary radiocarbon-based age model (2σ probability range in grey), which has been established using OxCal 4.1 (Ramsey, 1995, 2001, 2008) to evaluate the reliability of the varve chronology. Individual AMS ^{14}C dates from terrestrial plant macrofossils, which are included in the radiocarbon-based age model are given with their 2σ probability ranges.

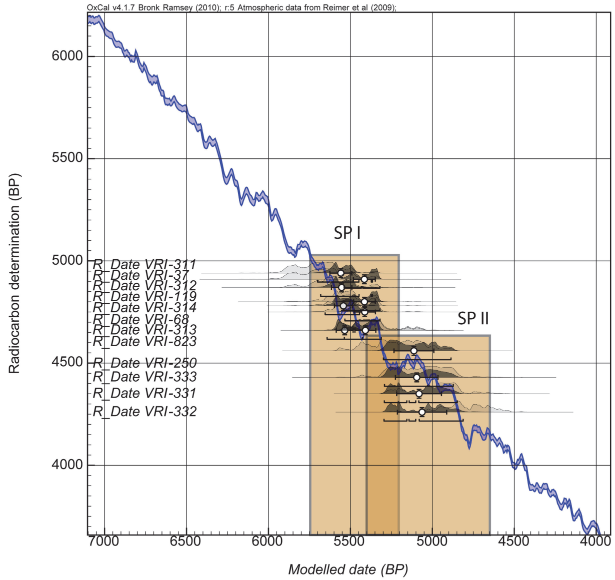

Fig. 3. Chronology of settling phases at Lake Mondsee. Twelve published AMS radiocarbon dates from three Neolithic lake-dwelling sites ("See", "Scharfling" and "Mooswinkel") were calibrated and used as input parameters for phase modelling with OxCal 4.1 (Ramsey, 2009). Two different settling phases can be distinguished: SP I from ca. 5750 to 5200 cal. yr BP and SP II from ca. 5400 to 4650 cal. yr BP.

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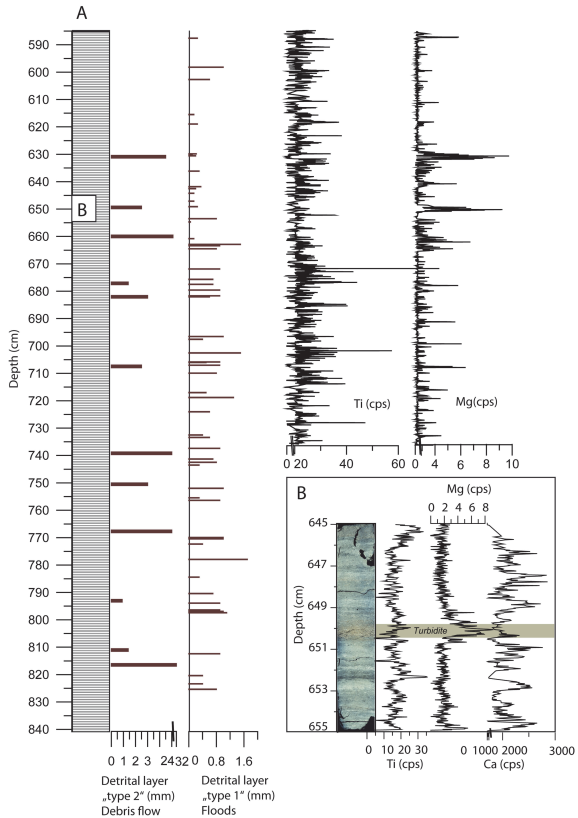

Fig. 4. Sediment data. **(A)** Lithology of the sediment core covering the interval between 585 and 840 cm with complementing detrital layer record (for further explanations see the main text), results of magnetic susceptibility measurements and µXRF element scanning data for titanium (Ti) and magnesium (Mg) for the interval between 585 and 736 cm. **(B)** Sediment microfacies as revealed from a thin section (645–655 cm) with a turbidite (detrital layer type 1) and corresponding µXRF data for Ti, Mg and Ca.

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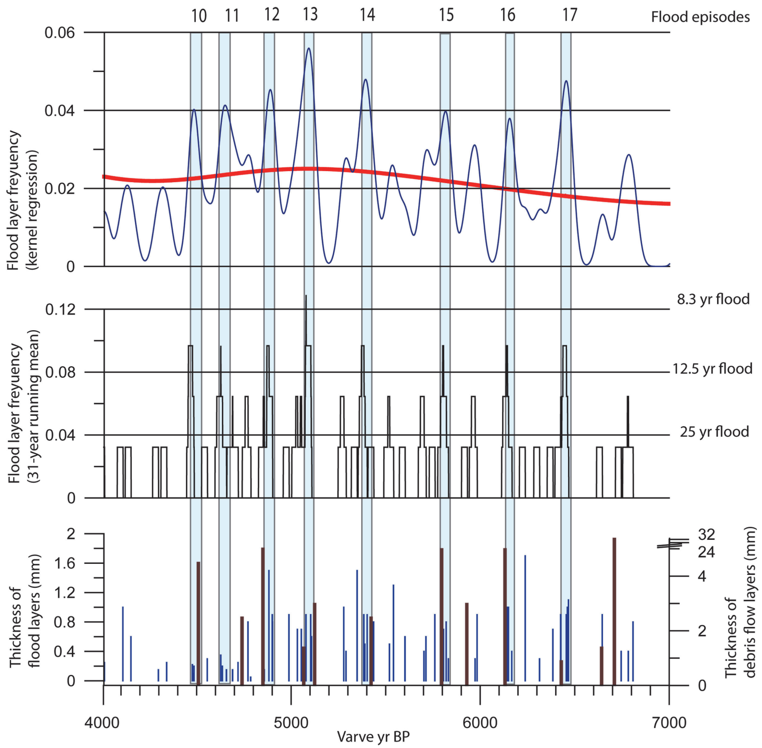

Fig. 5. Thickness of debris flow (detrital layer type 1) and flood layers (detrital layer type 2). Flood layer frequency as calculated by a 31 yr running mean and kernel regression with different bandwidths (blue line: 30 yr, red line: 500 yr). Eight main flood intervals (FE 10 to FE 17) are identified according to multi-decadal flood recurrence.

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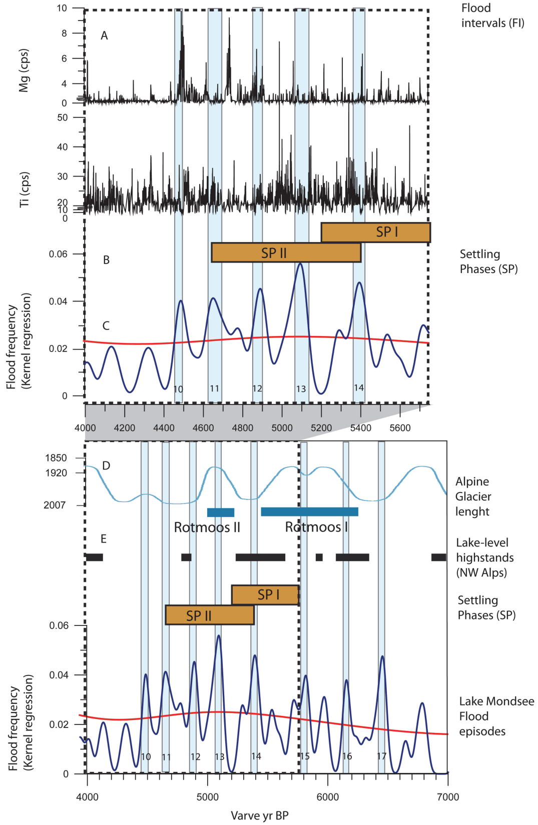

Fig. 6. Comparison of Lake Mondsee sediment data and identified flood episodes (FE 10 to FE 17) with other proxy data. **(A)** µXRF element scans for Ti and Mg from Lake Mondsee sediments. **(B)** settling phases SP I and SP II. **(C)** Flood occurrence (Kernel regression with 30 (blue) and 500 yr (red) bandwidth). **(D)** Austrian tree-line data (Nicolussi et al., 2005). **(E)** Alpine glacier lengths (Holzhauser, 2007) and phases of the Rotmoos Oscillation (Bortenschlager, 1970). **(F)** Lake-level highstands in the NW Alps (Magny, 2004).

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