HIGH-RESOLUTION SWISS LAKE RECORDS OF CLIMATE CHANGE

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presented by

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Table of contents

Table of contents ......................................................................................................................... i

List of figures and tables ................................................................................................................ v

Summary ......................................................................................................................................... viii

Zusammenfassung ............................................................................................................................. x

Chapter 1 - Introduction

1.1. Research motivation and general objectives ....................................................................... 2
  1.1.1. Tasks and importance within the CHIRP-initiative ...................................................... 3
1.2. Structure of the thesis ........................................................................................................... 5
1.3. References ............................................................................................................................. 8

Chapter 2 - Material and methods

2.1. Regional and climatological setting ..................................................................................... 12
  2.1.1. Lake Gerzensee ............................................................................................................. 13
  2.1.2. Lake Burgäschisee ....................................................................................................... 13
  2.1.3. Lake Soppensee ........................................................................................................... 14
  2.1.4. Lake Baldegg ............................................................................................................... 15
  2.1.5. Lake Zurich ................................................................................................................... 15
2.2. Methodology ......................................................................................................................... 16
  2.2.1. XRF core scanning ...................................................................................................... 17
  2.2.2. Chronologies ............................................................................................................... 18
2.3. References ............................................................................................................................. 19

Chapter 3 - High-resolution late-glacial chronology for the Gerzensee lake record (Switzerland): δ¹⁸O correlation between a Gerzensee-stack and NGRIP

Abstract .......................................................................................................................................... 24
3.1. Introduction ............................................................................................................................. 24
3.2. Study site and analytical methods ........................................................................................ 27
  3.2.1. Lake Gerzensee ............................................................................................................. 27
  3.2.2. Analytical methods ........................................................................................................ 28
### Table of contents

3.3. Method for establishing a high-resolution core chronology ............................................. 30
3.4. Results .................................................................................................................................. 38
3.5. Discussion ............................................................................................................................... 41
   3.5.1. Gerzensee lake marl ....................................................................................................... 41
   3.5.2. Terminology of events ................................................................................................. 42
   3.5.3. Age of Laacher See Tephra ......................................................................................... 45
   3.5.4. High-resolution palaeoclimatic implication .................................................................. 46
3.6. Conclusions ............................................................................................................................ 50
3.7. Acknowledgments .................................................................................................................. 51
3.8. Supplementary information .................................................................................................. 52
3.9. Discussion of event GI-1e2 ................................................................................................. 53
3.10. References ........................................................................................................................... 55

**Chapter 4 - High-resolution record of erosional input and environmental change during termination 1 at lake Gerzensee, Switzerland**

Abstract ........................................................................................................................................ 64
4.1. Introduction ............................................................................................................................ 65
4.2. Oxygen isotopes used as lateglacial chronological framework and indicator of climate change ........................................................................................................................................ 67
4.3. Study site .................................................................................................................................. 70
4.4. Methods ................................................................................................................................... 71
   4.4.1. Stable isotope analysis ................................................................................................... 71
   4.4.2. XRF core scanning ........................................................................................................ 72
   4.4.3. Biogenic silica (bSi) ...................................................................................................... 72
   4.4.4. Pollen analysis ............................................................................................................... 73
4.5. Termination 1 at lake Gerzensee ............................................................................................ 73
   4.5.1. Variation in erosion rates reflected in detrital input ....................................................... 75
   4.5.2. Variations in lake productivity reflected in biogenic silica ......................................... 76
   4.5.3. Variations in redox conditions reflected in iron variability ........................................ 78
4.6. Major transitions during Termination 1 ............................................................................... 79
   4.6.1. Onset of the Bølling .................................................................................................... 79
   4.6.2. Onset of the Younger Dryas ......................................................................................... 82
   4.6.3. Onset of the Holocene ................................................................................................ 83
4.7. Minor oscillations during the Bølling/Allerød ...................................................................... 84
4.8. Conclusion ............................................................................................................................... 87
# Table of contents

4.9. Acknowledgments ................................................................. 88
4.10. Supplementary information .................................................. 89
4.11. References ....................................................................... 90

## Chapter 5 - Holocene record for storminess in Central Europe

Abstract ....................................................................................... 102
5.1. Study site ........................................................................... 102
5.2. Manganese-rich sediments in Lake Burgäschisee ....................... 103
5.3. Climatic implications .............................................................. 105
   5.3.1. Long-term trend over the Holocene .................................. 105
   5.3.2. Variability in atmospheric circulation over Europe ............... 107
   5.3.3. Hemispherical variability of atmospheric circulation ............ 108
5.4. Conclusions ....................................................................... 111
5.5. Method summary .................................................................. 112
   5.5.1. XRF core scanning ......................................................... 112
   5.5.2. NanoSEM ....................................................................... 112
   5.5.3. XRD ............................................................................... 112
5.6. Acknowledgements ................................................................ 113
5.7. Supplementary information .................................................... 113
   S1. Material ............................................................................ 113
   S2. Chronology ....................................................................... 116
   S3. Twentieth Century Reanalysis data of the last 140 years .......... 117
5.7. References ....................................................................... 119

## Chapter 6 - Conclusion and Outlook

6.1. Conclusion ....................................................................... 124
6.2. Outlook ........................................................................... 127
6.3. References ....................................................................... 129

## Appendix

A.1. Age models ........................................................................ 111
   A.1.a. Burgäschisee ................................................................. 111
Table of contents

A.1.b. Soppensee .................................................................IV
A.1.c. Baldeggersee .............................................................VI
A.2. XRF data .................................................................VIII
A.2.a. Gerzensee .................................................................IX
A.2.b. Burgäschisee ............................................................XI
A.2.c. Soppensee ...............................................................XVII
A.2.d. Baldeggersee ...........................................................XXI
A.3. Sediment core images ..................................................XXV
A.3.a. Gerzensee Core GEM ...............................................XXV
A.3.b. Burgäschisee ...........................................................XXVI
A.3.c. Soppensee Core So08 ...............................................XXVIII
A.3.d. Baldeggersee Core Ba09 ...........................................XXX

Acknowledgements

Curriculum vitae
List of figures and tables

Chapter 1

Figure 1 – Organization and tasks of CHIRP1 ..............................................................................4

Chapter 2

Figure 1 – Map of Switzerland ....................................................................................................12
Figure 2 – XRF core scanner at ETH Zurich ..................................................................................18

Table 1 – Detailed information on studied lakes ........................................................................16

Chapter 3

Figure 1 – Map of Switzerland ....................................................................................................28
Figure 2 – Original δ¹⁸O records on depth scale ........................................................................30
Figure 3 – Schematic workflow for establishing the age depth model ........................................32
Figure 4 – Tie points correlating sediment cores .........................................................................34
Figure 5 – Relative weight in stacked record ...............................................................................36
Figure 6 – Correlation between NGRIP and stacked Gerzensee δ¹⁸O ..........................................37
Figure 7 – Original δ¹⁸O and sedimentation rates .......................................................................41

Table 1 – List of sediment cores ................................................................................................30
Table 2 – Terminology and timing of events ...............................................................................44
Table 3 – Overview over different lateglacial terminology .........................................................45

Supplementary Figure 1 – Relative weight in stacked record ...................................................53
Supplementary Figure 2 – Sensitivity analysis on Monte Carlo simulations ..............................53
Supplementary Figure 3 – Comparison of δ¹⁸O in different Greenland ice core records ...55
Supplementary Figure 4 – Comparison of parameters analyzed in GISP2 ice core ...........55

Chapter 4

Figure 1 – δ¹⁸O at Gerzensee and other archives .......................................................................69
Figure 2 – Map of Switzerland and study site at Lake Gerzensee ..............................................71
List of figures and tables

Figure 3 – High-resolution record of Termination 1 .......................................................... 74
Figure 4 – High-resolution record of three major transitions during Termination 1 .......... 81
Figure 5 – High-resolution record of Aegelsee Oscillation .............................................. 85

Supplementary Figure 1 – High-resolution record of the three transitions in Greenland and Gerzensee during Termination 1 ........................................................................... 89

Chapter 5

Figure 1 – Lamination in Lake Burgäschisee sediments .................................................. 104
Figure 2 – European proxy records of the past 7500 years ............................................. 106
Figure 3 – Hemispherical proxy records of the past 1500 years .................................... 109
Figure 4 – Atmospheric circulation patterns during LIA and MCA ................................ 110

Supplementary Figure 1 – XRF data .................................................................................... 114
Supplementary Figure 2 – Lamination with detrital layers ............................................ 115
Supplementary Figure 3 – XRD spectrum ........................................................................... 115
Supplementary Figure 4 – Age-depth model .................................................................... 116
Supplementary Figure 5 – Hemispherical mean vs. extreme wind speeds .................... 118
Supplementary Figure 6 – Decadal vs. seasonal mean wind speed ............................... 118
Supplementary Figure 7 – SLP, wind speed and 500 hPa GPH ........................................ 119

Supplementary Table 1 – 14C ages from the Burgäschisee record ................................. 117
Summary

Nowadays, climate change is a highly topical issue which is intensely discussed not only in science, but also in politics, economics, and everyday life. In order to understand the recent development and make applicable future predictions, detailed knowledge about past climatic variations is essential. Besides possible forcing mechanisms, insights into the natural environmental feedbacks and its rates of change are of great interest.

This PhD thesis investigates sediments from different Swiss lakes regarding their geochemical properties over the last ~15 000 years. Situated in central Europe in a region highly sensitive to changes in the atmospheric pathways, the study area is ideal to detect past climatic variability. In order to resolve the elemental composition of the lacustrine sediment cores, continuous high-resolution XRF core scanning (x-ray fluorescence) was applied. In combination with additional sedimentological and geochemical analyses such as stable isotopes, thin sections, XRD, NanoSEM and EDX on selected samples, the XRF data were set into mineralogical and sedimentological contexts. These new established records down to sub-decadal resolution illustrate different lake system evolutions and decisive paleoclimatic changes in great detail. The results of this thesis show that several geochemical fluctuations in Swiss lake records can be linked to hemispherical climate oscillations on decadal and centennial timescales.

Chapter 3 highlights the occurrence of four centennial cold oscillations during the Bølling/Allerød warm period seen as δ¹⁸O fluctuations. These phases can be correlated not only between different records of Lake Gerzensee but also over wide areas of the North Atlantic region. This correlation was used to build a robust chronology of the Gerzensee records and to refine the lateglacial terminology of events. The resulting δ¹⁸O stack from Gerzensee with its well established and detailed age-model has the potential to serve as an important reference curve of lateglacial climate variability for Central Europe.

Chapter 4 shows the δ¹⁸O-results together with the high-resolution elemental composition of the lateglacial Gerzensee sediments. A detailed comparison with the
composition of the Greenland ice cores indicates similarities in the evolution of the
dust flux in both regions at the transitions of the Younger Dryas where the dust influx
lags the temperature change. This suggests simultaneous large-scale changes in the
atmospheric circulation patterns in the whole North Atlantic region. In contrast, there
is a difference in the signature of the Greenland ice core record to the Gerzensee
sediments at the Aegelsee-Oscillation during the Bølling/Allerød, which poses new
questions about the fine structure of this cold event.

Chapter 5 demonstrates Manganese-rich lamination in sediments from Lake
Burgäschisee as a proxy for frequent wind-induced short-term mixing of the water
column. These phases occur simultaneously with frequent storminess at the Western
Mediterranean coast and increased dust transport from the Sahara desert to Europe.
In more detail, the past 1500 years show concurrent phases of increased windiness in
Central Europe, less landfalling subtropical hurricanes, and increased sea salt-ions
transported to Greenland. The resulting atmospheric pattern indicates large-scale
hemispherical changes towards more meridional pathways during these times.

In summary, this thesis provides new results on climatic variability in Switzerland
during the lateglacial and Holocene and proposes the involved teleconnections over
the northern hemisphere, such as large-scale variation of atmospheric pathways.
Nevertheless, further studies in sub-decadal resolution are needed to complete the
picture of the North Atlantic climate system in the past.
Zusammenfassung


Kapitel 4 vergleicht die $\delta^{18}O$ Kurve der spätglazialen Sedimente des Gerzensees mit Ergebnissen der hochaufgelösten Elementanalysen. Im detaillierten Vergleich zur Chemie der Grönland-Eiskerne wird deutlich, dass es Gemeinsamkeiten in der Entwicklung des Staubeintrags in beiden Regionen an den Übergängen der Jüngeren Dryas gibt, wobei der Staubeintrag verzögert zur Temperaturänderung reagiert. Dies weist auf gleichzeitige grossräumige Änderungen der Atmosphärenzirkulation in der Nordatlantik-Region hin. Im Gegensatz dazu zeigen sich Unterschiede in den Signaturen des Grönland-Eises und Gerzensee-Sediments während der Aegelsee-Schwankung innerhalb des Bølling/Allerøds, was weitere Untersuchungen erfordert.


Zusammenfassend zeigt diese Arbeit neue Überlegungen zu Klimaschwankungen in der Schweiz während des Spätglazials und Holozäns auf und verweist auf Verbindungen zu Prozessen auf der gesamten Nordhalbkugel, wie zum Beispiel grossräumige Änderungen der Atmosphärenzirkulation. Um das Verständnis des vergangenen Klimasystems der Nordatlantikregion zu vertiefen, werden allerdings dringend weitere Untersuchungen in sub-dekadischer Auflösung benötigt.
Chapter 1

Introduction
1.1. Research motivation and general objectives

For studying past environmental change on various temporal and spatial scales lake sediments present outstanding archives and complement other climate records from, for example, marine sediments, tree rings and stalagmites. It has been shown that sedimentological and geochemical properties of lacustrine sediments can give detailed information about palaeoclimate from a continental perspective (e.g. Bertrand et al., 2008; Brauer et al., 2008; Hodell et al., 2008; Lauterbach et al., 2011). Several previous studies in Swiss lakes have shown the great potential for climate studies over Central Europe by using different proxies in these sedimentological records (Ammann et al., 2000; Girardclos et al., 2005; Koinig et al., 2003; Lanci et al., 2001; Lister, 1988; Magny, 2004; Magny et al., 2001; Nussbaumer et al., 2011; Tinner and Lotter, 2001; Yu et al., 1997).

By the investigation of five different Swiss lake records regarding their detailed development through time, this PhD work provides further insights into their lake system evolution during the last ~15 000 years. This period ranges from the end of the last glacial until today and comprises the complete Holocene as well as Termination 1 including the Bølling/Allerød (B/A) and Younger Dryas (YD).

One main tasks of this thesis was the identification of the overall geochemical distribution, elemental composition and variation in different lake sediments in high resolution. The main method for achieving this goal was the X-ray fluorescence (XRF) core scanning technique (see chapter 2.2.1.). The resulting continuous high-resolution data sets demonstrate the great applicability of this modern method for analyzing the elemental composition of lacustrine sediment cores. Knowing the elemental composition enables the reconstruction of the mineralogical composition. With this knowledge, it becomes possible to reconstruct the different mechanisms leading to specific sedimentation, giving information about the environmental and climatic situation during a specific time. This lead to a better understanding of different physical, biological and geochemical processes within perialpine lakes in Switzerland and its influence on the lacustrine archives.
More specifically, the history of the catchment and erosion events could be reconstructed, and combining known data such as from palynological analysis with new high-resolution geochemical data enabled the reconstruction of past environmental and climatic changes in great detail. In a wider context, this thesis is one step further to unravel the forcing and feedback mechanisms of climate variability from a continental point of view by comparing the results with other archives over the North Atlantic region. These resulting high-resolution data sets of sedimentological and geochemical parameters eventually can be used as input for climate models.

To perform these tasks, this PhD thesis includes the following aspects:

- **Sedimentological properties**: What does the elemental composition reveal about the sedimentation regime and processes? To what extend does the type of lake system influence the elemental composition of the sediment?

- **Climate variability in Switzerland**: How does the climatic sensitivity differ among the various types of lake systems? What climate signatures in Swiss lakes sediments are of local, regional, or hemispherical origin? And how in detail are some major climatic key intervals and transitions expressed in Swiss lake sediments (e.g. Bølling/Allerød, Younger Dryas, Holocene climate fluctuations)?

- **Wider climatic implications**: What are the mechanisms driving climate change in Switzerland and Europe and to what extend is Swiss climate influenced by hemispherical influences such as the North Atlantic Oscillation?

### 1.1.1. Tasks and importance within the CHIRP-initiative

This PhD thesis is part of a CHIRP1 (Collaborative, Highly Interdisciplinary Research Project - Stage 1) at the ETH Zurich. The project is entitled “Lacustrine Sediments: High Resolution Archives for Geomagnetic Field Behavior and Paleoclimate” including the disciplines of Geophysical sciences (Geomagnetism, Rock and Paleomagnetism), Geology (Paleoclimatology, Sedimentology) and Environmental Sciences (Climatology, Cosmogenic radionuclides).
This part of the project had a considerable contribution to the other project parts by reconstructing sedimentologic, climatic and environmental evolution stored in the lacustrine archives through time in highest resolution, after establishing robust age models. This sedimentological investigation was needed for the correct interpretation of the $^{10}$Be and magnetic signal studied in the other project parts, since event depositions (i.e. turbidites, mass movements) or disturbed core sections do not contain meaningful environmental information. Thus, the in this study established chronologies, geochemical data sets and environmental interpretations are the basis for the works of the other project members (Kind, 2012; Mann, 2011; Panovska, 2012).

**CHIRP 1**

Lacustrine Sediments: High-Resolution Archives for Geomagnetic Field Behavior and Paleoclimate

![Diagram showing CHIRP 1 project components](image)

*Fig. 1. Organization and tasks of this CHIRP 1 project. The project part marked in red is presented in this thesis. Results constructed in this project part from Lake Soppensee (So), Lake Baldegg (Ba), and Lake Zurich (ZH) have been used in the other project parts and are mainly presented in the PhD theses of Jessica Kind (Kind, 2012), Mathias Mann (Mann, 2011), and Sanja Panovska (Panovska, 2012). Results from Lake Burgäschisee (Burg) and Lake Gerzensee (Gerz) have so far only been used in this thesis.*
Chapter 1 – Introduction

1.2. Structure of the thesis

This thesis “High resolution Swiss Lake records of climate change” contains six chapters. Each chapter comprises its own list of references, acknowledgements, and, if necessary, supplementary information. Chapter 1 and 2 provide a general introduction to the thesis topic, the study area, and the applied methodologies. Chapter 3 to 5 represent three individual manuscripts which are accepted, submitted, or in preparation for publication in peer-reviewed scientific journals. Chapter 6 gives an overall conclusion over the thesis and provides an outlook on further research in this field of interest. In addition, an Appendix supplies detailed information about the construction of the age models and the XRF data of the sediments not presented in chapter 3 to 5, but partially used in the other CHIRP 1 project parts.

The three manuscript can be summarized as follows:

- Chapter 3: "High-resolution late-glacial chronology for the Gerzensee lake record (Switzerland): $\delta^{18}O$ correlation between a Gerzensee-stack and NGRIP " by U. J. van Raden, et al. has been accepted for publication in the journal "Palaeogeography, Palaeoclimatology, Palaeoecology".

This manuscript presents an essential contribution to a special issue entitled “Early rapid warming” which is about to be published in the Journal "Palaeogeography, Palaeoclimatology, Palaeoecology". The issue focuses on biological and environmental proxies in the Gerzensee record concerning the relationship, timing, amplitudes and rates of the observed changes at the onset of and during the Bølling/Allerød period. Therefore a robust high-resolution chronology is crucial.

This manuscript presents a new high-resolution stacked $\delta^{18}O$ record from Gerzensee lake marl constructed from four parallel cores, covering the Bølling/Allerød (B/A) warm period. The applied stacking procedure reduces the noise of the individual records and highlights the common occurrence of four decadal to centennial cold oscillations during the B/A. The stacked $\delta^{18}O$ record was then used for establishing a detailed age-depth model over the B/A period by matching the Gerzensee $\delta^{18}O$ to the NGRIP $\delta^{18}O$ record.
On the one hand, the resulting chronology is the basis for a detailed comparison between the δ18O changes recorded in Lake Gerzensee and several climate and environmental fluctuations observed over the whole North Atlantic region. This study discusses in detail the timing and terminology of these climate events. On the other hand, the results are used to study the sedimentological and biological changes during the rapid warming and smaller climate oscillations at Lake Gerzensee during the B/A period (see other studies within this special issue). In addition, this new Gerzensee δ18O stack has the potential to serve as an important new reference curve of late-glacial climate for central Europe.

Chapter 4: “High-resolution record of erosional input and environmental change during Termination 1 at Lake Gerzensee, Switzerland” by U. J. van Raden, et al. has been submitted to the journal “Quaternary Science Reviews” and is currently in the peer-review process.

For this study, high-resolution XRF core scanning and stable isotope analyses was applied to the iconic sediment record from Lake Gerzensee, Switzerland, to determine the detailed pattern of climatic changes over Termination 1 (11-15 kyr) in Central Europe. Late-glacial sediments from Lake Gerzensee have been studied intensively over the past years and thus became a key location for studying the deglaciation period north of the Alps. Together with previously published proxy records from this and other lakes, this data demonstrates the changes in the environment and lake system during the late-glacial period and allows a detailed comparison of event successions regarding detrital influx, in-lake productivity and redox conditions.

The major climatic transitions of the B/A and YD and some minor oscillations were compared with the annually resolved Greenland ice core record from Steffensen et al. (2008). The novel findings about the similarity in dust influx at both locations at the onset and termination of the Younger Dryas have strong implications on the reconstruction of the atmospheric and climatic system. Furthermore, the different cold oscillations within the Bølling/Allerød were investigated and a specific succession of detrital input, in-lake productivity and temperature (as recorded in δ18O) could be observed for the Aegelsee Oscillation. Potentially, this study could
initiate further efforts in analyzing these short-lived climate swings also in the ice core records in order to better understand the forcing mechanism lying behind these cold oscillations.

With this unprecedented high-resolution elemental data set of the Gerzensee sediment we may come closer to unravel the detailed processes and the atmospheric circulation patterns over the whole North Atlantic region during deglacial times and periods of abrupt climate change and its impacts on the environment.

- **Chapter 5**: “Holocene record for windiness in Central Europe” by U. J. van Raden is in preparation for publication.

This manuscript shows a detailed record of Mn variability in sediments of Lake Burgäschisee throughout the Mid and Late Holocene. High Mn-counts identified by XRF core scanning are found in the well laminated sequences of the sediment, while low counts are detected in the non-laminated sediments. This study demonstrates that the formation of the Mn-rich laminae is related to short-term mixing events due to variation in wind stress on the lake surface. The Mn-record of Lake Burgäschisee is associated to a suite of records that have been attributed to changes in atmospheric circulation patterns. This comparison indicates a common response to large-scale atmospheric patterns in different archives over wide areas of the Northern Hemisphere. A detailed study of the last 2500 years strongly suggests a more meridional and variable atmospheric circulation pattern during the cold phase of the Little Ice Age. Using data of atmospheric parameters of the past 140 years, this manuscript discusses possible mechanisms leading to increased storminess in Central Europe observed in Burgäschisee sediments.
1.3. References


Chapter 1 – Introduction


Chapter 2

Material and methods
2.1. Regional and climatological setting

The different studied lakes are situated on the Swiss Plateau (Fig. 1) north of the Alps, which is extending between Lake Geneva and Lake Constance, as well as between Jura and the Prealps. All lakes have formed after the retreat of the glaciers from the Swiss Plateau about 18-15 kyrs ago (after the Würm glaciation) (Ivy-Ochs et al., 2008).

Geologically, the Swiss Plateau comprises the thick Tertiary Molasse sequence that accumulated north of the Alps due to the rapid erosion of the uplifting mountains. Most of the contemporary landscape of the Swiss Plateau has been modified by the glacier activity and fluvial incision during the Pleistocene, which reshaped the Molasse topography. Today, the lake catchments are dominated by glacial deposits which are mainly till, sand and gravel of reworked Molasse material, and thus represent a huge variety in composition from crystalline to carbonate components.

![Fig. 1. Map of Switzerland showing Lake Gerzensee (Gerz) and Lake Burgäschisee (Burg) as main study sites investigated in this thesis (large dots); in addition Lake Soppensee (So), Lake Baldegg (Ba), and Lake Zurich (ZH) are shown (small dots). Brown shaded area shows the region of the Swiss Plateau.](image)

Climatologically, the Swiss Plateau is situated in a transitional zone, subject to Atlantic, Arctic, continental, and Mediterranean influences between humid oceanic climate and continental temperate climate. The area shows distinct seasonality, which is typical for climatic conditions in Central Europe. With its location highly sensitive to the position of the Westerlies, Switzerland can be regarded a key area to detect changes in atmospheric pathways and climatic changes in the Northern Hemisphere.
2.1.1. Lake Gerzensee

Lake Gerzensee (Fig. 1) is a small (1100 m long, 300 m wide) eutrophic hard water lake in the Bernese Swiss Plateau at 603 m a.s.l. and is largely fed by groundwater (Guthruf et al., 1999). It was formed after the retreat of the Aare glacier and is now located on the S-E-slope of the “Belpberg” about 100 m above the two surrounding Aare- and Gürbe-valleys. With this position, the lake has a small catchment transporting very limited detrital input into the lake. Today, the lake is about 10.7 m deep, but during the late-glacial and early Holocene the water depth had been probably twice as deep as today (Eicher, 1979). This enables to recover authigenic lacustrine shallow water carbonates of late-glacial and early Holocene age also from today’s reed zone. Many biological (pollen, diatoms, pigments, chironomids, and others) and some geochemical (stable isotopes) proxy data are available from previous studies (Ammann et al., 2000; Eicher, 1987; Lotter et al., 2000; Lotter et al., 2012; Magny, 2001; Magny et al., 2007; Schwander et al., 2000; von Grafenstein et al., 2000; Wick, 2000) which have been considered in this work.

The comparison of δ¹⁸O results of the lake carbonates and the Greenland ice cores have shown similar trends and could be correlated with each other (Schwander et al., 2000; Siegenthaler et al., 1984; von Grafenstein et al., 2000). These δ¹⁸O trends together with marker horizons (such as the Laacher See Tephra), biozone boundaries, and carbon isotope analysis were used for establishing a robust chronology (chapter 3). About 5 m of mainly calcite-rich sediments were recovered in September 2008 for this project from the eastern shoreline and cover the period of about 8-15 kyr BP (Tab. 1). Results are presented in chapter 3 and 4 and Appendix A.2.a.

2.1.2. Lake Burgäschisee

Lake Burgäschisee (Fig. 1) is a small (surface area 0.21 km²) highly eutrophic lake at 465 m a.s.l. at the border of the cantons Bern and Solothurn. It was formed after the retreat of the Rhone glacier and today has only a very restricted catchment (3.2 km², highest elevation 75 m above lake level) (Guthruf et al., 1999). The lake consists of two basins, with 28 and 31 m maximum water depth, which is quite deep in contrast
to its surface area. Parts of Lake Burgäschisee surroundings have been intensively studied for archaeological purposes, since it was a settlement site during Early and Late Neolithic Age (Boessneck; et al., 1963; Müller-Beck, 2005). Naturally, the landscape around Lake Burgäschisee was composed of swamp and bogs. However, the complete ecosystem has been changed due to several lake level lowerings, most extensively in 1943, after a lake level lowering of 2 meters (Arn, 1945; von Büren, 1949; Weber, 1989). About 9 m of highly organic-rich sediments from the deepest basin were recovered in summer 2010 by the Paleoecology Group of the University of Berne. The age model was constructed by radiocarbon-dating and shows that sediment ages range from about 15000 years BP until today (Tab. 1, Appendix A.1.a.). Results from this study site are presented in Chapter 5 and Appendix A.2.b.

2.1.3. Lake Soppensee

Lake Soppensee (Fig. 1) is a small (800m long, 400m wide) eutrophic hard water lake at 595m a.s.l. in the Canton Lucerne. Lake Soppensee is largely fed by groundwater, and thus has only a small catchment (about 1.6 km²) limiting the detrital influx into the lake (Lotter, 1989). Its maximal water depth is 27 m and the oldest sediments are about 15000 years old with a ~5600 year lasting varved section between Bølling and Atlantic (~7000-13000 cal yr BP) (Fischer, 1996; Hajdas et al., 1993; Lotter, 1989; Lotter, 1991b). A suit of biological (pollen, diatoms, pigments, chironomids, and others) and some geochemical (stable isotopes) proxy data are available (Blockley et al., 2008; Fischer, 1996; Hajdas et al., 2000; Livingstone and Hajdas, 2001; Lotter, 1999; Lotter, 2001). Several climatic events (e.g. 8.2 kyr event), tephra layers (Laacher See Tephra (LST), Vaset/Killian Tephra) and biozones have been identified and allow for a good correlation between different cores (Hajdas et al., 1993; Hofmann, 2001; Lotter, 1991a; Lotter and Lemcke, 1999). These, together with additional radiocarbon ages, have been used for the establishment of the age model (Appendix A.1.b.). About 6 meter of organic rich and partially varved sediments covering the last ~15000 years until today were recovered in August 2008 from the deepest part of the lake (Tab. 1). Results are presented in the Appendix A.2.c. and were used in the PhD thesis of the other project parts (Kind, 2012; Panovska, 2012).
2.1.4. Lake Baldegg

Lake Baldegg (Fig. 1) is situated at 463 m a.s.l. in the Canton Lucerne in an overdeepened valley which has been created by the activity of the Reuss glacier. It has a water surface area of 5.2 km² and a maximum water depth of 66 m. Its watershed includes 67.8 km² (Wehrli et al., 1997). Several small streams feed the lake, which results in a detrital input higher than that of the other lakes discussed above. Seismic stratigraphy and earthquake-induced mass movement have already been studied (Becker et al., 2005; Monecke et al., 2006). About 6 meter of carbonate rich sediments including several event layers (e.g. slumps and turbidites) have been recovered in September 2009 from the deepest part of the lake which cover the last 15000 years until today (Tab 1, Appendix A.1.c.). The results are presented in the Appendix A.2.d. and were used in the PhD thesis of Jessica Kind and Sanja Panovska (Kind, 2012; Panovska, 2012).

2.1.5. Lake Zurich

Lake Zurich (Fig. 1) is situated at 406 m a.s.l. in the northern part of the Swiss Plateau. The lake is about 42 km long, 2-3 km wide and up to 137 m deep. Lake Zurich is separated into two basins: the “Obersee” and the “Untersee”. The upper ~13 m of the sediment cover have been deposited after the Linth Glacier had retreated to distant parts of the catchment (Lister et al., 1984). Previous studies deal with the sedimentary and environmental evolution of Lake Zurich (e.g. Bossard et al., 2001; Hsü and Kelts, 1984; Lister, 1988; Strasser et al., 2008). In addition, early research on cosmogenic nuclides had been performed (Schuler et al., 1991). In this project, the focus was on short cores recovered in 2009 and 2010 from different water depths covering the past ~150 years (Tab. 1). Detailed age models with seasonal resolution were established for each short core by varve counting. Results are presented in the PhD thesis of Mathias Mann (Mann, 2011).
Table 1: Detailed information on studied lakes

<table>
<thead>
<tr>
<th>Lake</th>
<th>Length of recovered sediment core</th>
<th>Time period</th>
<th>Results shown in</th>
<th>Age model *1) *2)</th>
<th>Core</th>
<th>Location *3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gerzensee</td>
<td>6 m</td>
<td>~8-16 kyr</td>
<td>- Chapter 3; Chapter 4</td>
<td>- δ18O correlation to NGRIP</td>
<td>- GEM</td>
<td>- 608 432 186 637</td>
</tr>
<tr>
<td>Burgäschisee</td>
<td>9 m</td>
<td>~0-16 kyr</td>
<td>- Chapter 5</td>
<td>- 14C, varve counting, LST</td>
<td>- Burg A, Burg B, Burg C</td>
<td>- 617 413 224 255</td>
</tr>
<tr>
<td>Soppensee</td>
<td>8 m</td>
<td>~0-16 kyr</td>
<td>- Kind, 2012; Panovsca, 2012</td>
<td>- 14C, LST (+ correlation to earlier dated parallel cores)</td>
<td>- So08-01, So08-02</td>
<td>- 648 726 215 724</td>
</tr>
<tr>
<td>Baldegg</td>
<td>14 m</td>
<td>~0-16 kyr</td>
<td>- Kind, 2012; Mann, 2011; Panovsca, 2012</td>
<td>- 14C, LST (+ correlation to earlier dated parallel cores)</td>
<td>- Ba09-01, Ba09-02, Ba09-03, Ba09-04, Ba09-05, Ba10-01, Ba10-04</td>
<td>- 662 292 227 809</td>
</tr>
<tr>
<td>Zurich</td>
<td>1 m</td>
<td>~last 200 yr</td>
<td>- Mann, 2011</td>
<td>- varve counting, 137Cs in short cores</td>
<td>- ZH10-08, ZH10-14, ZH10-21</td>
<td>- 687 117 238 167</td>
</tr>
</tbody>
</table>

*1) LST = Laacher See Tephra
*2) see Appendix A.1 for details
*3) Location given in Swiss coordinates

2.2. Methodology

The sediment cores were retrieved with the help of a freefall gravity corer for short sediment cores (max. ~1.5 m penetration) and a Niederreiter UWITEC-piston corer for cores of up to ~18 m length in 3 m sections. Initial core logging (MSCL = GEOTEK Multi-sensor core logger, at the Climate Geology Group, ETH Zurich) in 5 mm resolution was used to determine the petrophysical properties (GRAPE density = gamma-ray attenuation density, P-wave velocity, magnetic susceptibility) which was helpful for detailed correlation of several parallel cores of the same archive already before the splitting of the cores.

Subsequently, the cores were halved and documented. Core images were taken with a Jai CV L105 3 CCD Color Line Scan Camera with a resolution of 140 ppcm (350dpi) which was attached to the Avaatech XRF-core scanner of the Climate Geology Group, ETH Zurich. Based on the results of the early non-destructive methods (MSCL and optical investigation), core material was sampled (working halves) and distributed between the different partners based on a coordinated sampling strategy. This guaranteed that each sub-project could synchronize results with the other data sets.
For the sedimentological investigation, further analyses have been performed on certain time intervals of special interest to understand the exact environmental evolution.

- **XRD mineralogy**: powder X-ray diffractometer, Bruker, AXS D8 Advancce, equipped with a Lynxeye detector at the Institute of Geochemistry and Petrology, ETH Zurich on specific samples from Lake Soppensee, Burgäschisee, Gerzensee, and Baldegg.

- **Thin section evaluation**: 2x4 cm polished blocks and thin sections of sediment, imbedded in epoxy resins (LAROMIN C260, a cycloaliphatic diamine) on selected samples from Lake Gerzensee, Burgäschisee, and Baldegg.

- **Stable isotope analyses**: Thermo Fisher Scientific GasBench II coupled to a Delta V mass spectrometer at the isotope-geochemistry laboratory of ETH Zurich on lake marl from Lake Gerzensee.

- **NanoSEM/EDX**: Electron microscopy together with elemental analyzes performed at a NanoSEM (FEI Nova SEM 230 with SSD EDX with an energy dispersive X-ray spectrometer) at the EMPA in Dübendorf, on polished sediment-epoxy-blocks from Lake Gerzensee, Burgäschisee, and Baldegg.

### 2.2.1. XRF core scanning

Over the last years, X-ray fluorescence core scanning has emerged as a widely used and highly revealing method for non-destructive and fast acquisition of sediment compositions directly at the surface of split cores. In this thesis, all archive halves of all cores were analyzed in terms of their elemental composition using an AVAAITECH™ X-ray fluorescence (XRF) core scanner to obtain a high-resolution record. Before analysis, the sediment surfaces of the split cores were carefully smoothed in order to get a maximum quality and resolution. Then, the sediment surface was covered with a 4 µm thick Ultralene® SPEX CertiPrep-foil to avoid contamination of the XRF measurement unit and desiccation of the sediment. All air bubbles and all wrinkles in the foil were thoroughly eliminated.
The following elements could be analyzed:

- **Al, Si, P, S, K, Ca, Ti, Mn, and Fe**: with 10 kV voltage and no filter. Cl, V, Cr were not used, since they seemed to be close/below the detection limit with the applied settings. Rh counts are an artifact resulting from the Rh-X-ray-source of the scanner, but could be used to control the stability of the measurements.

- **Br, Rb, and Sr**: with 30 kV voltage and thick Pd-filter. Zn, Mo, Pb, Bi were not used, since they seemed to be close/below the detection limit with the applied settings.

Intensities of each element were reported as total counts per area. Further information and results are presented in Appendix A.2.

---

### 2.2.2. Chronologies

Radiocarbon dating on terrestrial organic macrofossils has been performed at the Accelerator Mass Spectrometer (AMS) at the ETH/PSI Ion Beam Physics Group. These datings together with tephra layers of known age i.e. the Laacher See Tephra (LST) (Blockley et al., 2008; Hajdas et al., 1995) are used to build robust core chronologies. At Lake Soppensee, Lake Baldegg, and Lake Zurich, which already have excellent age constrains, our sediment records are linked to those existing chronologies correlating event marker horizons and sediment features (Lotter, 1989; Lotter, 1991a; Lotter, 2001; Monecke, 2004). The age models are documented in the Appendix A.1. for each lake.
2.3. References


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Chapter 3

High-resolution late-glacial chronology for the Gerzensee lake record (Switzerland): $\delta^{18}O$ correlation between a Gerzensee-stack and NGRIP

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Chapter 3 – High-resolution late-glacial chronology

Abstract

Oxygen-isotope variations were analyzed on bulk samples of shallow-water lake marl from Gerzensee, Switzerland, in order to evaluate major and minor climatic oscillations during the late-glacial. To highlight the overall signature of the Gerzensee δ¹⁸O record, δ¹⁸O records of four parallel sediment cores were first correlated by synchronizing major isotope shifts and pollen abundances. Then the records were stacked with a weighting depending on the differing sampling resolution. To develop a precise chronology, the δ¹⁸O-stack was then correlated with the NGRIP δ¹⁸O record applying a Monte Carlo simulation, relying on the assumption that the shifts in δ¹⁸O were climate-driven and synchronous in both archives. The established chronology on the GICC05 time scale is the basis for (1) comparing the δ¹⁸O changes recorded in Gerzensee with observed climatic and environmental fluctuations over the whole North Atlantic region, and (2) comparing sedimentological and biological changes during the rapid warming with smaller climatic variations during the Bølling/Allerød period. The δ¹⁸O record of Gerzensee is characterized by two major isotope shifts at the onset and at the termination of the Bølling/Allerød warm period, as well as four intervening negative shifts labeled GI-1e2, d, c2, and b, which show a shift of one third to one fourth of the major δ¹⁸O shifts at the beginning and end of the Bølling/Allerød. Despite some inconsistency in terminology, these oscillations can be observed in various climatic proxies over wide regions in the North Atlantic region, especially in reconstructed colder temperatures, and they seem to be caused by hemispheric climatic variations.

3.1. Introduction

The transition from the last glacial to the present interglacial (Termination 1, ~15-10 kyr BP) is characterized by several major and minor climatic oscillations which had strong impacts on marine and terrestrial environments (Ammann et al., 1994; Brauer et al., 2000; Hughen et al., 1996; Karpuz and Jansen, 1992; Litt et al., 2003; Lowe et al., 1994). In lacustrine settings, stable isotope analysis of carbonates is one of the best methods to identify and reconstruct those terrestrial climatic and environmental
changes. The oxygen-isotopic composition of inorganic lake carbonate is mainly influenced by (1) the δ¹⁸O of precipitation in the watershed, (2) the water temperature, (3) the hydrologic balance of the lake, and (4) biological activity within the lake (Bernasconi and McKenzie, 2007; Leng and Marshall, 2004). Whatever the exact causes affecting the isotopic composition of lake carbonates, major and minor fluctuations in δ¹⁸O are observed during the late-glacial in various lacustrine archives of the Northern Hemisphere (e.g. von Grafenstein et al., 1999; Yu and Wright, 2001) and seem to dominantly reflect variations in summer temperatures.

The three most prominent and therefore most extensively studied oxygen isotope shifts are the abrupt increase from low δ¹⁸O during the Oldest Dryas (GS-2) to less negative δ¹⁸O values during the Bølling/Allerød (B/A) interstadial (GI-1), followed again by low δ¹⁸O during the Younger Dryas (GS-1) and a sharp increase at the onset of the Holocene (Andrič et al., 2009; Eicher, 1987; Lotter et al., 1992; Rasmussen et al., 2006; Riezebos and Slotboom, 1984; Schwander et al., 2000; Siegenthaler et al., 1984). The strong similarity between δ¹⁸O and several other climate proxies in terrestrial, marine, and ice-core records suggests that these shifts are climate-controlled and thus synchronous over wide regions (Benson et al., 1997; Hoek and Bohncke, 2001; Hughen et al., 1996). This has already been suggested by pioneering work of Siegenthaler, Eicher, Oeschger, and Dansgaard in 1984, showing a very similar pattern in the oxygen-isotope record of lake marls from Lake Gerzensee, Switzerland and in the Dye 3 Greenland ice-core (Siegenthaler et al., 1984).

Since the development of analytical techniques enables additional and more highly resolved data sets, several minor fluctuations in δ¹⁸O could be observed. The present study focuses on the B/A δ¹⁸O record with its internal fluctuations. Three to four decadal to centennial climatic oscillations during this period were recognized in the Greenland ice-core (Björck et al., 1998; Brauer et al., 2000; Lowe et al., 2008) and in marine records (Asioli et al., 1999; Fletcher et al., 2010; Karpuz and Jansen, 1992) of the North Atlantic region. In terrestrial records, these oscillations have been observed in Europe, e.g. in various lakes in Switzerland (Ammann, 2000; Lotter et al., 2000; von Grafenstein et al., 2000), southern Germany (von Grafenstein et al., 1999), Great Britain (Brooks and Birks, 2000a; Jones et al., 2002; Lang et al., 2010; Marshall et al.,
2002), and Scandinavia (Brooks and Birks, 2000b; Paus, 1988; Paus, 1989). Several records in North America also reflect 3 to 4 short-lived environmental shifts during the B/A, mainly due to colder temperatures (Marshall et al., 2002; Nolan et al., 1999; Whittington et al., 1996; Yu, 2007; Yu and Wright, 2001).

It is remarkable that the cold phases of different duration and amplitude are all well reflected in terrestrial response over wide regions. This leads to the basic assumption that the warming and cooling during the late-glacial interstadial were hemispheric and that their recording in the oxygen isotopes of the two distant archives of Greenland ice and Gerzensee lake marl was synchronous and without delays. Quasi-simultaneous occurrence of major changes is indeed likely since the climatic conditions in Greenland and on the European continent are synoptically dependent, e.g. by the North Atlantic Oscillation (Hurrell et al., 2003). Also, a mechanism that would lead to a very similar but time-shifted climatic pattern at different geographical sites, is unlikely, since a climatic pattern delayed by more than the synoptic time scale would be dampened and altered.

Thus, because of the expected synchronicity of these climatic shifts in the North Atlantic region, $\delta^{18}O$ fluctuations can be used as time markers and can be correlated not only within one archive but also between different records from different regions. This approach was used for establishing an age-depth model for the new high-resolution Gerzensee record, because building a radiocarbon-based chronology was not possible due to the absence of terrestrial macrofossils in the studied cores. In addition, precise conventional radiocarbon dating would be difficult because a plateau of constant radiocarbon age during the early part of the Bølling (Ammann and Lotter, 1989; Reimer et al., 2009) prevents a precise age assignment by $^{14}C$-dating. In addition, annual laminations and tephra layers (except for the Laacher See Tephra) to further constrain the age are not present during the period of interest.

The NGRIP $\delta^{18}O$ record on the Greenland Ice Core Chronology 2005 (GICC05) (Rasmussen et al., 2006) was used for building the age-model for the B/A. This record seems most suitable for a comparison with the Gerzensee record, since (1) no European $\delta^{18}O$ record is well enough established to meet the conditions necessary for
high-resolution correlation during the late-glacial period, (2) the Greenland ice cores are some of the best absolutely dated archives for the period of interest, and (3) the NGRIP record was adopted by the North Atlantic INTIMATE group as a regional stratotype (Lowe et al., 2008). The resulting high-precision chronology of the lake marl in Gerzensee is the basis for further studies (this volume) that compare sedimentological and biological changes and to evaluate response times and mechanisms and reconstruct environmental development during times of rapid climatic change.

3.2. Study site and analytical methods

3.2.1. Lake Gerzensee

![Fig. 1. A) Map of Switzerland with location of Lake Gerzensee
B) Map of Gerzensee with coring location.](image)

Gerzensee is a small kettle-hole lake on the Swiss Plateau at 603 m a.s.l. (46°49’56.95”N, 7°33’00.63”E) (Fig. 1). The lake is situated on a ridge separating the valleys of the Aare and the Gurbe’ rivers. Its low catchment relief protects the lake from major erosional input. The small catchment area of 2.6 km² (Lotter et al., 2000) is underlain by the till of the Aare glacier over Miocene Molasse sandstone. Today the lake has a small artificial inflow from the North, a lake surface of 25.16 ha and a maximum water depth of 10.7 m. The surroundings of Gerzensee became ice-free about 17-18 kyr BP (Ivy-Ochs et al., 2008; Preusser, 2004). Because the water level was higher during the late-glacial than today (Eicher, 1979) late-glacial shallow-
water carbonates occur underneath about 1 m of soil in today’s reed zone. This late-glacial marl formed a littoral sub-aquatic terrace, comprised mainly of authigenic carbonates (both inorganically precipitated and bio-induced) with some molluscan shell debris but very little organic matter and detrital material. Four parallel cores were recovered on the eastern shoreline of Lake Gerzensee in the years 1976 (labeled: GE III), 1992 (GEAB), 2000 (GEJK), and 2008 (GEM) (Fig. 1, Tab. 1).

### 3.2.2. Analytical methods

The sampling resolution for continuous stable-isotope analyses ranged between 5 and 0.5 cm (see Tab. 1 for details). For all cores the sampled material was freeze-dried, and shells were carefully removed from the sediment before analysis to minimize biogenic calcite contributions to the isotope signal of the inorganic calcite (Fig. 2). The term “bulk carbonate” (δ\(^{18}\)O\(_{\text{bulk}}\)) is here used for the fine-grained inorganic lake marl. Carbon and oxygen isotopic compositions were measured in the bulk carbonate of four different cores of the Gerzensee marl (Tab. 1). Resulting values are reported in the conventional delta notation with respect to VPDB.

For core GEM, the analyses were made in the isotope-geochemistry laboratory of ETH-Zurich on a Thermo Fisher Scientific GasBench II coupled to a Delta V mass spectrometer. About 350 µg of powdered sample was placed in 12 ml vacutainers, flushed with helium, and were reacted with 5 drops of 104 % phosphoric acid at 72 °C. The instrument was calibrated with the international reference materials NBS 19 (δ\(^{13}\)C = +1.95 ‰, δ\(^{18}\)O = -2.2 ‰) and NBS 18 (δ\(^{13}\)C = -5.05 ‰, δ\(^{18}\)O = -23.1 ‰). The analytical reproducibility based on repeated measurement of an internal standard was better than ±0.08 ‰.
**Fig. 2.** Original $\delta^{18}O$ records on individual depth scales. The Laacher See Tephra (LST, yellow vertical line) was set as a common reference level to 272 cm core depth.

**Table 1**

List of sediment cores indicating the depth intervals and resolution of the individual stable-oxygen records used in this study. *1: Laacher See Tephra (LST) as reference level was set to 272 cm core depth.

<table>
<thead>
<tr>
<th>Core name</th>
<th>Coring date</th>
<th>Analyzed interval (cm) *1</th>
<th>Sampling interval (cm)</th>
<th>Sampling resolution (cm)</th>
<th>Coring method</th>
<th>Thickness start Bolling LST (cm) *1</th>
<th>Thickness LST-start YD (cm) *1</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEM</td>
<td>Sept. 2008</td>
<td>70.5-406.5</td>
<td>70.5-406.5</td>
<td>0.5</td>
<td>Uwitec piston corer (⌀ 5.8 cm)</td>
<td>73</td>
<td>16</td>
</tr>
<tr>
<td>GEJK</td>
<td>Sept. 2000</td>
<td>270-414</td>
<td>336-390</td>
<td>0.5</td>
<td>Streif modified Livingstone corer (⌀ 8 cm)</td>
<td>102</td>
<td>- no data -</td>
</tr>
<tr>
<td>GEAB</td>
<td>Oct. 1992</td>
<td>169-364</td>
<td>191-201</td>
<td>0.5</td>
<td>Streif modified Livingstone corer (⌀ 8 cm)</td>
<td>92</td>
<td>19</td>
</tr>
<tr>
<td>GE III</td>
<td>June 1976</td>
<td>112-414</td>
<td>245-275</td>
<td>2.5</td>
<td>Streif modified Livingstone corer (⌀ 8 cm)</td>
<td>77</td>
<td>20</td>
</tr>
</tbody>
</table>
For the cores GEJK, GEAB, and GE III each sample of <50 mg of carbonate was reacted with 95% phosphoric acid (H₃PO₄) at a constant temperature of 50°C for 1 hour to produce CO₂, which was then analyzed for its ¹⁸O/¹⁶O ratio with a mass spectrometer (Finnigan MAT 250) at the University of Bern (Siegenthaler and Eicher, 1986). The scale was calibrated and checked regularly with international standards available through the International Atomic Energy Agency (IAEA). The analytical precision is about 0.02 ‰ for δ¹⁸O. Long-term stability is controlled by an internal laboratory standard (marble) with -2.85 ‰ on the VPDB scale. Over several decades the values of the internal standard are within 0.1 ‰. The carbonate content was generally around 80-90 % with a minimal value of 45 %.

3.3. Method for establishing a high-resolution core chronology

The Gerzensee chronology was established by applying an “event stratigraphy” approach in order to correlate the Gerzensee lake marl record with the well-dated δ¹⁸O isotopic records from Greenland ice cores. Whittaker et al. (1991) describe event stratigraphy as the procedure of correlating strata on the basis of geologically short-lived events such as volcanic eruptions or climate excursions, which are expressed in a great variety of records and therefore can be used for correlation of different proxies (e.g. pollen, insects, and isotopes) and localities.

To highlight the overall signature of the Gerzensee δ¹⁸O marl record and to eliminate sampling or analytical artifacts, a stack of four parallel δ¹⁸O records was established that was then matched to the NGRIP δ¹⁸O record. Figure 3 shows the workflow in which (a) the original δ¹⁸O data sets from GEJK, GEAB and GE III were correlated to a common depth scale (i.e. the GEM depth scale), (b) then mathematically resampled to the same resolution, and (c) combined to a weighted stack. This stack was then (d) visually correlated to NGRIP δ¹⁸O and partially fine-tuned (e) by a Monte Carlo method. Finally, (f) a chronology for each original δ¹⁸O core record was determined by using the now established relationships of the original depth to the common depth scale (established in step b) and of the common depth scale to NGRIP-age (established in step e).
Chapter 3 – High-resolution late-glacial chronology

For the above-described procedure, AnalySeries 2.0 (Paillard et al., 1996) was extensively used. For resampling (steps b and f), simple linear interpolation was applied. For matching two or more records the lineage function was utilized (steps a and d). In the following each step is discussed in detail.

**a - Correlation of four sediment cores**

The four individual sediment cores GEM, GEJK, GEAB, and GE III were first correlated by synchronizing the most prominent isotopic shifts at the beginning and end of Bølling/Allerød interstadial (Fig. 4, tie point 1, 2, 11, 12). The records were fine-tuned during the B/A by the pollen abundances of Betula, Pinus, Salix, Gramineae and Juniperus, which were correlated whenever they were available (Fig. 4, tie points 4-13).

The tie points are mainly based on minima and maxima of the pollen abundances. The higher the sampling resolution and number of available records the smaller the uncertainty in the position of tie points. Thus, the uncertainty of the position of the tie points is mostly less than 2 cm, where all four records are available. However, tie points 6 and 7 are defined mainly by synchronizing the gradients in Pinus and Betula abundances of only two available records (GE III and GEJK), which leads to an uncertainty within a few centimeters regarding the exact position of these tie points.
A distinct 6-8 mm thick volcanic ash layer visible in all four cores, stratigraphically and chemically identified as the Laacher See Tephra (LST), is used as an additional independent marker and set as a reference level to 272 cm core depth corresponding to the center of the tephra layer (Fig. 4, tie point 3). As the δ¹⁸O record from GEM had the highest resolution, a constant sampling resolution of 0.5 cm over the investigated time interval, the GE III, GEAB, and GEJK cores was transferred on the GEM depth scale.

b - Resampling to a common depth scale

After correlation to a common depth scale (GEM depth scale), the four records were resampled by linear interpolation to have a uniform 0.5 cm resolution. That was a requirement for the following stacking procedure.

c - Weighted stacking of the individual δ¹⁸O lake marl records

The original sampling resolution and therefore also the temporal resolution varied between the four isotopic records (Tab. 1). It is likely that the records with the highest resolution (continuous 0.5 cm for entire GEM and parts of GEJK) exhibit the most details in the δ¹⁸O shifts, whereas GE III with continuous sampling in a resolution of 2 cm represents a smoothed record. Therefore, a weighting based on the original sampling resolution was made in which a doubling in sampling resolution leads to a doubling of importance of the record in the stack (Fig. 5a). Thus, the stack is dominated by the δ¹⁸O signal of GEM and partially GEJK.

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Fig. 4. (next page) Tie points (numbered circles) correlating four sediment cores of the Gerzensee lake marl to a common GEM depth scale. A) δ¹⁸O records, 1: δ¹⁸O low, 2: δ¹⁸O peak, 3: Laacher See tephra, 11: δ¹⁸O peak, 12: δ¹⁸O low B) Results from pollen analyses, 4: Pinus low, Betula high, 5: Pinus and Betula trends, 6: Pinus and Betula trends, 7: Betula low, Gramineae high, 8: Betula low, Salix high, 9: Betula high, Salix high, 10: Juniperus trend, Gramineae trend, 11: Juniperus peak, Salix low, 12: Juniperus low, 13: Juniperus trend, Salix low.
The weighted sample mean (=weighted stack) is:

\[
\bar{x}_w = \frac{\sum_{i=1}^{n} (w_i x_i)}{\sum_{i=1}^{n} w_i}
\]

with:
- \(\bar{x}_w\) = weighted sample mean
- \(w_i\) = allocated weight for the given data
- \(x_i\) = observed value for a given data.

The standard error of the weighted stack has been estimated by using the equation:

\[
s_{\bar{x}} = \sqrt{\frac{\sum_{i=1}^{n} w_i (x_i - \bar{x})^2}{(n-1) \sum_{i=1}^{n} w_i}}
\]

with:
- \(s_{\bar{x}}\) = standard deviation of the weighted stack

(eq. 1.105a, p. 160 in Sachs, 1997).

Considering the small degree of freedom (number of stacked records -1) in the standard error calculation we multiply \(s_{\bar{x}}\) obtained with eq. (3) by Student’s t value for \(p= 0.317\) (confidence level corresponding to one standard deviation of a normal distribution). This results in a consistent confidence interval throughout the record.

Because the relative weighting of each single record may vary within the stack, we checked that the basic characteristics of the stacked record did not change. By comparing the weighted stack with the normal averaged stack, it was assured that there were no artificial steps or distinct signatures at the positions where there are changes in the relative weighting of the stack (Supplementary figure 1).
**Chapter 3 – High-resolution late-glacial chronology**

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**Fig. 5.** A) Relative weight of the four $\delta^{18}O$ records in the stack.  
B) Stacked $\delta^{18}O$ Gerzensee record with standard deviation of the weighted stack.  

Yellow vertical line at 272 cm sediment depth marks the position of the Laacher See Tephra.

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**d - Correlation to NGRIP**

The chronology was established by matching the Gerzensee and Greenland isotopic records. This relies on the assumption that changes in $\delta^{18}O$ in Greenland and Europe occurred simultaneously. For better comparison with terrestrial, marine, and archeological records that are expressed in radiocarbon years before AD 1950, the GICC05 timescale (Rasmussen et al., 2006), which is originally in years b2k (before 2000 AD), was converted to years BP (before 1950 AD). In the Greenland ice core record the age and depth values refer to the bottom of each interval. However, the depths in the Gerzensee isotope data refer always to the middle of each sampling interval. Therefore, the NGRIP ages calculated for the middle of each interval were used for matching the two records.
First, the prominent $\delta^{18}O$-shifts at the beginning and end of B/A were correlated. Then, three minor oscillations visible clearly in both, the NGRIP and Gerzensee $\delta^{18}O$ records, were correlated (dashed red lines in Fig. 6). Applying this approach, one needs to be aware that the resulting timescale for the Gerzensee record is not independent but is based on a correlation to NGRIP (NGRIP-dating-group, 2006) and GICC05 (Rasmussen et al., 2006).
**e - Monte Carlo simulation**

For detailed correlation between the two δ¹⁸O records of Gerzensee and Greenland, we applied a Monte Carlo method, as described in Schwander et al. (2000). This method is a stochastic technique that matches two time series by randomly shifting the time points of one series until the best correlation between the two series is reached. Constraining parameters used in this study are: a minimum of correlation coefficient of 0.4, a total of 50 points for the correlation (size of window), and a range of slope between two records of 0.4 and a maximum age shift of ±25 years.

First, we selected a subset of each time series, including the two distinct major shifts in δ¹⁸O at the beginning and end of the B/A, resulting in subsets of 183 δ¹⁸O values for Gerzensee (i.e. between ca. 12,800 and 14,800 BP) and 124 for NGRIP record (i.e. between ca. 12,500 and 15,000 BP). Then the age window of the lake subset was placed at one end of the ice core subset, and a preliminary age from the previously established visual match was assigned to the first data point of the Gerzensee subset. To find the best correlation of the two records, all points of the window, except for the first one, varied randomly within meaningful limits (Schwander et al., 2000). A significant correlation was considered when the correlation coefficient (r) exceeded a threshold of 0.4. Once the simulation determined a group of values with the highest correlation coefficient, the window was shifted one data point, with the first point fixed to the age of the best correlation point, and the randomization process repeated. In this manner the window was subsequently shifted until the end of the record was reached. The resulting ages of the new time scale are the averaged values from the best correlations of each window position. In order to achieve a high level of accuracy, the simulations were performed on 75,000 trials per step and a total of 15 runs through the time series.

Two main factors may significantly affect the results of the Monte Carlo simulation: (1) the total width of the windows, which is the number of correlation points and (2) the maximum age shift of each point of the window. Thus, sensitivity tests for both variables were performed by first varying the width of the window (4, 8, 25, 50 correlation points) and then the maximum age shift (10, 50, 100 years), while keeping all the other parameters constant. A maximum age shift of ±25 years and a
maximum of 50 correlation points were chosen to avoid possible overtuning (Supplementary figure 2). All other parameters were set as in Schwander et al. (2000). Finally, to account for the direction in which the window moved through the record, the analysis was run for both directions of the moving window (each in 10 replicates).

In principle, the Monte Carlo method can be expected to be less subjective than visual matching. However, it can be observed that the differences between the results generated by the visual matching and the Monte Carlo method are marginal and within uncertainties (less than ±15 years) (Fig.6), supporting the objectivity of the performed visual match. Nevertheless, one must be aware of the limits of such matching approaches. In fact, it is often possible to achieve a good correlation of very different records if no constraints are imposed on stretching and compressing the time axis. This can easily lead to overtuning, that is matching of signals that are not causally linked. A subtle choice of constraints is therefore the basis of any time-series matching.

f - Resampling for individual chronologies

The relationship between the original depth scales and the common GEM depth scale (established in step b) and the relation of the GEM-depth scale to NGRIP age (established in step e) was used to determine the relation between the original depth and the NGRIP age. This leads to individual chronologies for each sediment core (Fig. 7).

3.4. Results

Figure 6 shows the high-resolution chronology for the δ¹⁸O Gerzensee stack established by correlating δ¹⁸O of Gerzensee and NGRIP. The temporal resolution of the Gerzensee stack, which is strongly based on the spatial resolution of 0.5 cm in the GEM and GEJK cores, is 8.2-14 years during the period of interest. This confirms that the comparison with the NGRIP record, which has a temporal resolution of 20 years,
is appropriate. Although the Laacher See Tephra is not found in the Greenland ice record, its age can be determined from our isotope correlation to 13034 yr BP.

Signal noise, erratic sedimentation features (such as small scale redeposition of sediment), and possible sampling artifacts (such as small shell fragments within a bulk sample) can be minimized by stacking the four available data sets. Since the stacked oxygen isotopic record of the lake carbonate is smoother than each original data set and mainly reflects overall features, it best represents 13 local isotope zones, GRZ \textsubscript{ibulk} 1 being the oldest (Fig. 6). The $\delta^{18}$O-values abruptly rise from about -9 %o before 14685 a BP (GRZ \textsubscript{ibulk} 1) in ~95 years (GRZ \textsubscript{ibulk} 2) to -5.8 %o (GRZ \textsubscript{ibulk} 3) and then continuously decrease during the following ~1500 years (GRZ \textsubscript{ibulk} 4-10). There is a final peak of -6.3 %o at about 12880 years (GRZ \textsubscript{ibulk} 11) before the abrupt drop in $\delta^{18}$O during ~150 years (GRZ \textsubscript{ibulk} 12) leading to values of around -9 %o (GRZ \textsubscript{ibulk} 13).

A significant feature of the stacked $\delta^{18}$O record is the pattern of short-term oscillations imposed on the long-term trend. Three distinct fluctuations with pronounced negative isotopic shifts can be identified in the stacked isotopic record, as well as in all individual records. GRZ \textsubscript{ibulk} 6 at a sediment depth of 322-314 cm (14044-13908 yr BP) shows an abrupt drop from about -7 to -8 %o in $\delta^{18}$O values. GRZ \textsubscript{ibulk} 8 at a sediment depth of 298-293 cm (13624-13522 yr BP) shows a slightly gradual decline towards a final distinct depression, which is followed by a sharp increase in $\delta^{18}$O from about -7.5 to -8.4 %o. GRZ \textsubscript{ibulk} 10 at a sediment depth of 282.5-269 cm (13274-12989 yr BP) shows a gradual low from about -7.2 to -8.3 %o in $\delta^{18}$O. Thus, GRZ \textsubscript{ibulk} 6 records the largest $\delta^{18}$O shift, whereas the oscillation in GRZ \textsubscript{ibulk} 10 lasts the longest. All three observed distinct minor oscillations reach down more than halfway to earlier stadial $\delta^{18}$O values. An additional minor oscillation (GRZ \textsubscript{ibulk} 4, 336-326cm, 14439-14183 yr BP) can be observed in the stacked isotopic record with only a small decrease in $\delta^{18}$O values of about 0.5 %o.

Comparison of the individual original data sets shows that the sediment thickness from the beginning of the Bølling to the LST ranges between 73 and 102 cm in the four cores (Tab. 1). The individual records of GEM, GEJK, GEAB, and GE III (Fig. 7)
show similar sedimentation rates mostly ranging between \(\sim 3\) and \(6\) cm/100 yr during B/A. Relatively low sedimentation rates occur in the Bølling period.

Intermediate sedimentation rates characterize the middle and late Allerød, with a slight increase after the deposition of the LST. Increased sedimentation rates occur in the first half of the Allerød in all four cores, however with especially high rates of up to \(15\) cm/100 years in core GEJK between \(\sim 13.6\) - 13.8 kyr BP. This observation indicates some variability in the sedimentation rates during the late-glacial, even though the cores were recovered within a small area. Small-scale lateral heterogeneity in lacustrine settings was documented earlier by Lotter et al. (1997). This period of high sedimentation rate lies within a longer period of rather low-to-intermediate lake levels (Magny, this volume). Whether these variations in

Fig. 7. Original \(\delta^{18}O\) record and sedimentation rates (in gray) vs. GICC05 time scale (converted to years before 1950 AD) for each individual Gerzensee core.
sedimentation rate during low lake level arise from small-scale increased calcite production in shallower water or from patchy redistribution of carbonates on the shallow platform remains unclear.

3.5. Discussion

3.5.1. Gerzensee lake marl

$\delta^{18}O$ of inorganic carbonates in small/medium open lakes dominantly reflect $\delta^{18}O_{\text{water}}$ during calcite precipitation (see Ito, 2001; Leng and Marshall, 2004; Teranes et al., 1999 for review). Authigenic calcite inorganically precipitates in late spring/early summer in the epilimnion because of changes in lake water chemistry (increased temperature, algal activity, and pH). However, inorganic carbonates may also be formed as an extra-cellular by-product during photosynthesis. For example, Characeae and other micro and macrophytes actively remove bicarbonate from the lake system, leading to the formation of inorganic calcite, which typically encrusts the plants (von Grafenstein et al., 2000). For the Gerzensee lake marl record it has been shown that the fine-grained carbonate matrix is composed of a mix of authigenic calcite and of disaggregated calcitic encrustations (von Grafenstein et al., 2000) that commonly form on the stems and oogonia of the aquatic macrophyte Chara, as also seen in other lakes (Apolinarska and Hammarlund, 2009). It is debated in the literature to what extent calcite encrustations precipitate in isotopic equilibrium with the lake water. Especially for the oxygen isotopes of encrustations the opinion differs between isotopic equilibrium (Ito, 2001) and disequilibrium (Pelechaty et al., 2010). However, the $\delta^{13}C$ consistently is shown to be enriched in calcite encrustations. During sample preparation, biogenic carbonate (i.e. ostracods, gastropods) was removed, but it was not possible to discriminate between authigenically formed carbonate and fine particles of Chara encrustations.

Disregarding the precise formation of the inorganic calcite, the similarity of the lake records and the excellent correlation with the NGRIP record validate the $\delta^{18}O_{\text{bulk}}$ proxy for reconstructing climatic changes. In addition, $\delta^{18}O_{\text{bulk}}$ has in general the same signature as the $\delta^{18}O$ of discrete Chara encrustations and molluscan Pisidium shells, which have been observed to represent mainly the $\delta^{18}O_{\text{water}}$ in which the
calcite precipitates. This is closely related to $\delta^{18}O_{\text{precipitation}}$ and thus to mean annual air temperature (von Grafenstien, this volume). A large input of detrital carbonates potentially influencing the isotopic record of the lake marl seems insignificant during B/A for two additional reasons: Firstly, Gerzensee is situated on a moraine ridge and at a topographically high position, and it therefore has only a small catchment which is strongly limiting the detrital input (Ruch, 2001). Secondly, the sampled material originates from a littoral lake marl platform and most of the available detrital input would focus in the center of the lake basin and unlikely in shallow water.

### 3.5.2. Terminology of events

Application of the concept of synchronous large-scale climatic changes makes it possible to correlate and compare different late-glacial chronostratigraphic units of various records in the North Atlantic region. A chronostratigraphic unit is a body of sediment strata representing the sediments deposited during a specific interval of geologic time (Mangerud et al., 1974). Thus, chronostratigraphic units in theory are of same age in different regions. However, due to uncertainties in the original studies or misinterpretations by later scientists, as well as regional differences, much confusion exists about the use and implication of the various terminologies during the late-glacial period (de Kleerk, 2004; Litt et al., 2003) (Tab. 2, Tab. 3). Some confusion probably was caused when proxy records were temporally not resolved high enough and therefore missed short-term climatic oscillations of decadal- to centennial-scale duration. Another source for confusion arises from using the same name for chronozones, which represent same time intervals, and biozones, which represent same biological assemblages and may not be synchronous over wider distances. Some earlier studies also use terms such as “Middle Dryas” (Bock et al., 1985) or “Earlier/Late Dryas” (Van Geel et al., 1989) instead of the conventional terms “Oldest/Older/Younger Dryas”, which might have led to additional confusion.
Table 2
Terminology and timing of events during the late-glacial period for the oxygen isotope records from Gerzensee lake marl and Greenland ice cores. Ages are presented on GICC05- time-scale (converted to years before 1950 AD).

<table>
<thead>
<tr>
<th>Local isotope zonation</th>
<th>Classical terminology used in Swiss lakes</th>
<th>Modified Greenland terminology</th>
<th>Gerz stack age (yr BP)</th>
<th>Gerz stack depth (cm)</th>
<th>GEJK depth (cm)</th>
<th>Lowe et al. 2008, GICC05 (yr BP)</th>
<th>INTIMATE Greenland terminology</th>
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<tr>
<td>13</td>
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<td>12710</td>
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<td>LST*4</td>
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<td>12846</td>
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<td></td>
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</tbody>
</table>

*1: High sampling resolution enables definition of transitions as separate zones.
*2: Diffsers from Greenland terminology, since transitions (GRZ ibulk 2 and 12) were added as separate zones.
*3: Also known as IACP (Lehman and Keigwin, 1992), parallel to Killarney Oscillation in North America (Levesque et al., 1993).
*4: Laacher See Tephra.
*6: GI-1e was separated into sub-zones (this study), term "Inter Bølling Cold Period" (IBCP) was avoided since it has been used inconsistently (e.g. Karpuz and Jansen, 1992; Hughen et al., 1996).

Table 3 shows several examples of chronological terms used for naming events and periods during the late-glacial (also called Termination 1) in the North Atlantic region. The stadial (GS-2) preceding the late-glacial interstadial is commonly called Oldest Dryas but Pleniglacial in northern and northwestern Germany. The stadial (GS-1) succeeding the late-glacial warm period is consistently called Younger Dryas. The late-glacial interstadial itself (GI-1) is named Meiendorf/Bølling/Allerød in northern and northwestern Germany, whereas in most other areas of the North Atlantic region it is consistently called Bølling/Allerød period. However, the definition of the described boundary between the Bølling and the Allerød varies in different records (see Tab. 3).
Two to four cold phases during the late-glacial interstadial are recognized in various records of the North Atlantic region (Tab. 3). They can be correlated with the Greenland ice core records. The earliest cold oscillation during the Interstadial (e.g. GRZ \textsubscript{bulk} 4) lies within GI-1e and is named Bølling Cold Period I (BCP I) in the Norwegian Sea (Karpuz and Jansen, 1992) but is not described in many other records. The first widespread cooling (e.g. GRZ \textsubscript{bulk} 6) is recognized in most records from the North Atlantic region by e.g. lower δ\textsuperscript{18}O values and can be correlated with GI-1d in the Greenland records. The third observed cooling event (e.g. GRZ \textsubscript{bulk} 8) lies within GI-1c in Greenland and is named GI-1c2 in the Eifel region in Germany (Brauer et al., 2000). The last pronounced δ\textsuperscript{18}O fluctuation in the B/A (e.g. GRZ \textsubscript{bulk} 10) correlates with GI-1b in Greenland.
To circumvent further confusion and clarify relations, a modified Greenland-terminology is applied in addition to the conventional terminology for the high-resolution record at Gerzensee. We are aware that the INTIMATE event stratigraphy should not replace regional stratigraphic schemes, but rather be used as a standard against which regional stratigraphic schemes are compared as suggested by the North Atlantic INTIMATE group (Lowe et al., 2008). However, it seems that the Greenland terminology is widely used, and introducing new local terms would rather increase confusion in cases where a solid correlation to the Greenland chronology can be established. The highly resolved Gerzensee marl record allows for the description of additional fluctuations, and the determination of the transitions at the onset and termination of the B/A interstadial as separate zones. Therefore, the terminology was slightly modified at the B/A transitions (Fig. 6). This facilitates further studies (this volume) on the timing and response mechanisms of environmental changes to climatic change.

3.5.3. Age of Laacher See Tephra

A unique time marker at the end of the Bølling/Allerød warm period is the tephra layer of the phonolitic Laacher See eruption in the Eifel region, Germany. The Laacher See Tephra (LST) is widespread in central and northern Europe (Bogaard and Schmincke, 1985). In Gerzensee, it can be stratigraphically correlated in all four Gerzensee cores as a gray layer of 6 to 8 mm thickness with discrete volcanic glass shards, which have been identified chemically by Walter-Simonnet et al. (2008).

The isochronous nature of the LST allows the new Gerzensee chronology, established by event-stratigraphical correlation with NGRIP, to be compared with other independently dated records (i.e. outcrops, tree rings and lake sediments). The age of the LST in the stacked Gerzensee record is 13,034 years BP. This age can be compared with direct age dating on single crystals of the LST by laser-fusion $^{40}$Ar/$^{39}$Ar analysis, resulting in an age estimate of 12,900 ± 560 yr BP (Van den Bogaard, 1995). High-precision $^{14}$C data obtained from the outer rings of trees that were buried by the LST about 60 km away from the eruptive center result in an age of 11,063 ± 12
conventional radiocarbon years BP (Friedrich et al., 1999). Calibration of this radiocarbon age with Oxcal 4.1.7 (Bronk Ramsey, 2009) and INTCAL09 (Reimer et al., 2009) yields a calibrated age range of 12,769-13,098 cal. BP (two sigma range). Another method to determine the age of the LST is by dendrochronology, by which the observed 192-year difference between the Laacher See Eruption and the onset of the Younger Dryas (Kaiser, 1993) is combined with the recently determined onset of the YD (~12,760 cal yr BP in Hua et al., 2009). This would result in an age for the LST of approximately 12952 cal yr BP. The LST is also found in numerous European lakes, among them varved lake records, revealing slightly younger ages for the LST. An independent varve chronology from the Meerfelder Maar and Holzmaar, Germany, dates the LST at 12,880 (± 120) yr cal BP (Brauer et al., 1999). Blockley et al. (2008) calculate the age of the LST in Soppensee, Switzerland, to 12,975–12,743 cal BP, taking the combined age estimates of two models, the P.Sequence by depth and by varve spacing (INTCAL 04). Hajdas and Michczynski (2010) determine a calendar age of 12,735–12,878 cal BP for LST in Soppensee (INTCAL09).

The age of the LST in our study of 13,034 cal yr BP is slightly older than that suggested by the latest studies from Soppensee (Blockley et al., 2008; Hajdas and Michczynski, 2010) and Meerfelder Maar (Brauer et al., 2008), but well within error of tree ring age estimation (Friedrich et al., 1999). However, taking the error range of layer counting in the NGRIP ice cores into account (about ± 150 yr, Rasmussen et al., 2006), this age is well within range of previous studies.

3.5.4. High-resolution paleoclimatic implication

Palaeoclimatic interpretation from δ18O of lacustrine carbonates from lakes is challenging, since direct calibration with temperature or δ18O in precipitation is difficult. Changes in δ18O of inorganic lake carbonates can be attributed to (1) changes in water temperature, (2) changes in history/source of the water, (3) variations in biological activity, or (4) changes in hydrology of the lake (Bernasconi and McKenzie, 2007; Leng and Marshall, 2004). Von Grafenstein et al. (2000) postulated that the hydrology at Gerzensee and thus the evaporative enrichment of δ18Owater was rather
constant, with approximately 2 ‰ during most of the Holocene and late-glacial. Thus, we exclude hydrological changes and assume mostly climatic causes to be the dominant factor controlling changes in $\delta^{18}O_{\text{bulk}}$. Schmid (2011) applied clumped isotope analyses to the Gerzensee late-glacial carbonates and found an increase of 2.6 ‰ in $\delta^{18}O_{\text{water}}$ at the onset of the Bølling and a decrease of 2.2 ‰ at the transition from the BA to the YD. These oxygen-isotope shifts in the lake water seem not to correlate with clumped-isotope temperatures, which would reflect water temperatures during calcite precipitation. However, $\delta^{18}O_{\text{water}}$ seems to be directly related to changes in $\delta^{18}O_{\text{precipitation}}$, mainly reflecting mean annual air temperatures. Thus, the $\delta^{18}O_{\text{bulk}}$ can be used as a proxy for annual air temperature change in the region around Gerzensee (Schmid, 2011). This observation is in accordance with the temperature reconstructions and interpretation of von Grafenstein et al. (this volume; 2000) and Lotter et al. (2000; 2012).

With a sampling resolution down to 0.5 cm the resulting data set yields a temporal sampling resolution of ~10 years during the Bølling/Allerød. This permits a detailed comparison between the $\delta^{18}O$ record from Gerzensee and the records from other late-glacial archives, as well as for the reconstruction of abrupt climatic changes.

Comparison of the four Gerzensee $\delta^{18}O$ records shows some similarities and differences (Fig.7). The three conspicuous $\delta^{18}O$ oscillations (GRZ $i_{\text{bulk}}$ 6, 8, and 10) are visible in all records, even at low sampling resolution (GE III). However, GRZ $i_{\text{bulk}}$ 6 has a different structure in GEAB, which might be due to variations in the shallow-water sedimentation or a sampling artifact. GRZ $i_{\text{bulk}}$ 8 has slightly different structures in all four cores, but all show a gradual decline towards a final distinct depression, which is followed by a sharp increase in $\delta^{18}O$. GRZ $i_{\text{bulk}}$ 10 has in all four cores a wide gradual $\delta^{18}O$ depression. The oldest oscillation GRZ $i_{\text{bulk}}$ 4 is less pronounced than the other ones and might be an overestimation of noise in these records. However, other proxies such as for lake-level fluctuations (Magny, this volume) at Gerzensee as well as other archives (Karpuz and Jansen, 1992; Marshall et al., 2002) in the North Atlantic region show a distinct cold-temperature oscillation during the early part of the interstadial.
These century-scale cold events during a general cooling trend of the Bølling/Allerød warm period in the Gerzensee δ¹⁸O stacked record are similar to several other records in the North Atlantic region, despite differences in archives, geographical settings, or the proxies used. However, not always all four oscillations can be observed, most likely due to insufficient stratigraphic resolution. In many records only GI-1b and -1d are described, since those are the most pronounced cold oscillations (Tab. 3).

Friedrich et al. (2001) observe several depressions in tree ring width from trees in Germany, Switzerland, and Italy that most probably reflect colder temperatures in southern and central Europe during growing season. The floating tree ring record shows decadal scale cold periods, i.e. a period of 25-39 years, assumed to be similar to GI-1d (Aegelsee Oscillation) and a period of ~60 years equivalent to GI-1b (Gerzensee Oscillation). According to our chronology, GI-1d and GI-1b resulted in cooling periods of centennial scale, i.e. ~135 and 285 years, respectively. The discrepancy between the tree ring and lake marl records may arise from inconsistent definitions of the event boundaries and different sensitivities of the systems to temperature change. In addition, the tree-ring record also contains depressions not reflected in the Gerzensee lake marl δ¹⁸O record, which might reflect specific local terrestrial conditions or be a result of higher resolution of the tree-ring record.

The three prominent oscillations during B/A have also been observed in the grayscale record of marine sediments from the Cariaco basin north of the Venezuelan coast. This record is interpreted as a proxy for a change in the trade wind strength in the tropics in response to changes in the temperature gradient between high latitudes and the tropical North Atlantic (Hughen et al., 1998). Whatever the cause, the minor cooling events during the B/A appear to affect both low and high latitude regions in the same manner. However, Marshall et al. (2002) note a relative difference in magnitude of temperature values of the events at different sites. In the terrestrial archives (lakes and ice), all records show event GI-1d (Aegelsee Oscillation) as the largest, while in marine records GI-1b (Gerzensee Oscillation) is the most pronounced. Also Rensssen and Isarin (2001) point out, that the magnitude of temperature change expected during the late-glacial period strongly depends on the location of a site in
Europe (the latitude, altitude, and proximity to an ice sheet). It is therefore quite possible that such minor oscillations are recorded more strongly at sites closer to ecotonal boundaries (Heegaard et al., 2006) located at higher latitudes or altitudes (Brooks and Birks, 2000a; Brooks and Birks, 2000b; Heiri et al., 2007).

The origin of these widespread short-term climate oscillations and the role of internal climatic variability, solar activity, volcanism and other forcings are still under debate. Considering the length and abruptness of the δ¹⁸O depressions during B/A, several geological and modeling studies suggest a disruption of the oceanic thermohaline circulation by meltwater discharge from the continental ice sheets as a likely mechanism for abrupt cooling of the North Atlantic region during the late-glacial and Holocene (Clark et al., 2001; Donnelly et al., 2005; Fleitmann et al., 2008; Kleiven et al., 2008; Nesje et al., 2004; Renssen et al., 2007; Teller et al., 2002). Changes in the North Atlantic thermohaline circulation would have a strong influence on the atmospheric circulation and moisture transport pathways, as discussed by several authors (e.g. Brauer et al., 2000; Yu, 2007). Björck et al. (1996) and Thornalley et al. (2011) state that the minor oscillations during the late-glacial and early Holocene coincide with ocean ventilation minimum phases. However, clear evidence for the origin of the freshwater input and interrelation of freshwater outbursts and cooling events is sparse and not yet consistent. Standford et al. (2006), Bard et al. (1996), and Clark et al. (1996) suggest that the Meltwater pulse 1A (MWP-1A) coincides with the abrupt cooling of one of the short-term cooling events, whereas several other authors predate the MWP-1A concurrent to the sharp late-glacial warming (Deschamps et al., 2012; Kienast et al., 2003; Nesje et al., 2004; Weaver et al., 2003). Donnelly et al. (2005) present evidence from North America that a meltwater discharge may have played an important role in triggering the last cold oscillation of the B/A by reducing the thermohaline circulation. Nesje et al. (2004) show that three centennial-scale climatic deteriorations during the B/A were probably linked to three corresponding oceanic rerouting events which caused reduction in thermohaline circulation and cooling in the North Atlantic region. However, further evidence for the source and mechanisms of freshwater discharges are needed.
In addition, Yu (2007) noted that the general trend during the B/A warm period is different among various records. While the δ^{18}O at Crawford Lake and the Greenland ice cores show a declining trend during the B/A warm period, the records from Gerzensee, White Lake, Ammersee and Cariaco show a plateau-like Bølling–Allerød warm period (Yu and Eicher, 1998). These trans-Atlantic similarities and differences hint at the existence of a strong spatial gradient in climatic changes presumably because of changes in moisture source (Yu, 2007). This is in accordance with Magny (this volume) who observes generally higher lake levels during periods of low δ^{18}O in the lake carbonates, which might imply changes in the precipitation pattern coinciding with a shift in the thermocline of the lake water.

3.6. Conclusions

A large number of terrestrial records are available from the late-glacial period (Termination 1, ~15-10 kyrr BP), which give highly detailed pictures of past environmental change. Nevertheless, the Greenland oxygen-isotope records are so far regarded as the best-dated and most-detailed high-resolution climate proxy for the North Atlantic region. Our new developed stacked oxygen isotope record from Gerzensee serves as an additional terrestrial record from continental Europe during the Bølling/Allerød period with an exceptional high resolution of ~10 years/sample.

After synchronization of changes in pollen assemblages and major isotopic shifts of four records from the same archive, a stack of the according δ^{18}O datasets highlights the overall common features of the Gerzensee lake marl with four negative oscillations. Thus, this stacked record is most suitable for comparison with other climatic proxies in other regions. For this comparison, a high-resolution chronology for the Bølling/Allerød period was constructed by matching the Gerzensee δ^{18}O stack with the NGRIP δ^{18}O record, first visually and then refined with the help of a Monte Carlo simulation. According to our new chronology, the Laacher See Tephra is dated to 13,034 BP. This is slightly older than previous published ages, but well within the error range of other age estimates. This new chronology was used for other studies (this volume) dealing with the comparison of sedimentological and biological changes
and the evaluation of response timing and may hint at to response mechanisms and environmental development during times of rapid climatic change.

Since the stacked record is more representative for the lake record than each single dataset it mainly reflects overall features highlighting the presence of three distinct and one less expressed δ18O-depression during the B/A. Since the Greenland terminology is widely and consistently used, this terminology was slightly modified and transferred to the Gerzensee records. Thus, the observed δ18O-depressions correspond to GI-1e2, -1d, -1c2, and 1b. The last three distinct oscillations show a change of about 1 ‰ and thus have amplitudes of about one fourth to one third of the δ18O shift at both terminations in and out of the Bølling/Allerød period. These oscillations have been shown to be parallel to many other records due to hemispherical climate variations probably caused by freshwater discharges into the Atlantic. Further studies are needed to verify the timing, distribution, and definite causes and feedbacks of these centennial- to decadal climatic variations in the North Atlantic region during the warming of the late-glacial period.

3.7. Acknowledgements

We thank Brigitta Ammann for critical discussion of the manuscript, Pim van der Knaap for discussing the pollen data, Sebastian Breitenbach for assisting with the stable isotope analyses at ETH Zürich, and Robert Hoffmann, Willy Tanner, Axel Birkholz and Stefanie Templer for assistance during fieldwork. Logistical support from the Study Center Gerzensee is cordially acknowledged. Financial support was provided by an ETH research grant – CHIRP1 (CH1-02-08-2).
3.8. Supplementary information

Supplementary figure 1. A) Relative weight of the four δ¹⁸O records in the stack. B) Comparison of building the δ¹⁸O stack by weighted (black) and unweighted (red) average of the individual oxygen isotope records. Arrows show locations where relative weight of the stack changes. No artificial “jumps” in the weighted stack occur compared to the unweighted average.

Supplementary figure 2. Sensitivity analysis to investigate possible effects of overtuning in Monte Carlo simulations. We first varied the number of correlation points (size of the window), while keeping constant all the other parameters (A). Same with the maximum age shift (B). Possible overtuning effect (e.g. no offset) occur with number of correlation points <15. Also, we observe a marked offset (>50 years) with window age shift >100, resulting in chronological inversions. In the final version, we kept number of correlation points = 50 and age shift +/- 25.
3.9. Discussion of event GI-1e2

This paragraph is an addition to the published manuscript. There has been an important issue with the use and the refinement of the INTIMATE Greenland isotope terminology, especially event GI-1e2. There was need for discussion, whether the GI zonation is an appropriate terminology, since this specific event cannot clearly be observed in the $\delta^{18}$O of the NGRIP ice core. When going strictly after Lowe et al. (2008) suggestion, I would have to give this a local name.

I agree, that in the NGRIP-$\delta^{18}$O record no phase of lower values can be observed during GI-1e. However, in the cores GISP2 and GRIP a small cold oscillation can be identified (suppl. fig. 3). In addition, the temperatures for central Greenland reconstructed from GISP2 (Alley, 2000) and also the K- and Ca-ion concentrations in GISP2 (Mayewski et al. 1997) (suppl. fig. 4) indicate a period of slightly colder temperatures during GI-1e.

The manuscript discusses the fact that “GI-1e2” cannot be observed in as many records as the later oscillations. This may be due to different sensitivities of the archives and the methods used. “GI-1e2” seems to be a very subtle oscillation with only slightly colder temperatures and therefore with less impact on the environment. However, since there is a hint towards a cold period during the earliest stage of the B/A also in Greenland (GISP2 and GRIP), we still think that the term “GI-1e2” is appropriate. We believe, that introducing a new local term (or even taking one of the already used ones) would lead to more confusion instead of increasing clarity in the event-stratigraphy and terminology of events.
Supplementary figure 3. Comparison of δ¹⁸O records of different Greenland ice core records. Blue bars indicate minor cold oscillations during the Bølling/Allerød (GI-1). Red line marks event GI-1e2 discussed in paragraph 3.9. Data: GICC05_NRIPP_GRIP_GISP2_data_20yr_6april2008 (Rasmussen et al., 2008).

Supplementary figure 4. Comparison of reconstructed temperature, Ca-concentration and K-concentration in the GISP2-icecore record. Blue bars indicate minor cold oscillations during the Bølling/Allerød (GI-1). Red line marks event GI-1e2 discussed in paragraph 3.9. Data: GISP2 Ice Core Temperature and Accumulation Data (Alley, 2000).
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Chapter 4

High-resolution record of erosional input and environmental change during Termination 1 at Lake Gerzensee, Switzerland

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1 in preparation for publication
Abstract

High-resolution XRF core scanning and stable isotope analyses were applied to sediments from Lake Gerzensee, Switzerland, to determine the pattern of climatic changes over Termination 1 (11-15 kyr) and demonstrate influences on the environment and lake system during the lateglacial period. Temporal resolution of the elemental record varies between 3.3 and 5.6 years allowing a detailed comparison of event successions regarding detrital influx, in-lake productivity and redox conditions. Detrital input, as reflected by the sum of the elements Al, K, Zr, Rb and Ti, shows a decreasing trend during the early part of the Bølling/Allerød until the onset of the cold oscillation GI-1c2 (13.6 kyr BP). This coincides with the full establishment of stable pine forest in the vicinity of the lake and documents the strong linkage between vegetation and erosional input. The major climatic transitions of the Bølling/Allerød and Younger Dryas could be compared in great detail with the Greenland ice core records (e.g. Steffensen et al., 2008). Increased detrital fluxes, interpreted as increased aeolian input, are recorded for Gerzensee and Greenland during the Younger Dryas. The highly resolved records from both sites reveal eminent similar patterns at the onset and termination of the Younger Dryas at which the detrital input lags the temperature change by several decades. These similarities in dust proxies suggest that changes of large-scale atmospheric circulation patterns and variation in gustiness likely dominated the aeolian flux over the larger North Atlantic region. In addition to the major climate shifts of Termination 1, the four minor cold oscillations of the Bølling/Allerød were studied in detail. But only the Aegelsee Oscillation (GI-1d) revealed a pattern in the elemental proxies in the Gerzensee record. Interestingly, the detrital input leads the δ^{18}O record, which is so far not documented for the Greenland ice core records. The other three Bølling/Allerød cold oscillations were either too weak or the environment was too stable so that no impact on the elemental record of Gerzensee could be observed.
4.1. Introduction

One major technological development in paleoclimatic studies over the last decades is the implementation of innovative core scanning techniques allowing continuous and highly resolved analyses down to sub-annual time scales. Only with these new techniques, short-term leads and lags between proxy records at climate transitions can be resolved and used to better understand the behavior of the climate system during rapid shifts. In the last years, especially Termination 1 (~15-10 kyr) received much attention as new high-resolution studies could show that major climatic transitions occurred within a few years (Brauer et al., 2008; Steffensen et al., 2008). Termination 1, the so called last late glacial, was a period of major and minor rapid climatic changes that had strong impacts on marine and terrestrial environments (e.g. Karpuz and Jansen, 1992; Ammann et al., 1994; Lowe et al., 1994; Hughen et al., 1996; Brauer et al., 2000; Litt et al., 2003). It is characterized by a rapid warming at the onset of the Bølling/Allerød (onset of Greenland Interstadial 1 (GI-1), ~14,600 yr BP), a distinct cooling at the onset of the Younger Dryas (onset of Greenland Stadial 1 (GS-1), ~12,800 yr BP), and again a rapid warming at the onset of the Holocene (~11,600 yr BP) (e.g. Dansgaard et al., 1993; Lowe et al., 1994; Renssen and Isarin, 2001; Vandenberghhe et al., 2001; Walker, 2001; Lowe et al., 2008). Steffensen et al. (2008) were able to show in the NGRIP Greenland ice core detailed sequences of events over these three above mentioned late glacial major climate transitions. Within 1 to 3 years, the moisture source of the precipitation switched its mode, whereas air temperature raised more gradual over a 50 years period. Also the dust pattern showed a specific succession, which allowed some conclusions about the relative timing between a wetting in the Asian dust source area and the abrupt climate changes observed in Greenland.

In addition to these large shifts, up to four minor climatic cooling events during the Bølling/Allerød are described in marine (e.g. Hughen et al., 1996) and lacustrine archives (e.g. Benson et al., 1997; Brauer et al., 2000; Litt et al., 2001; Yu and Eicher, 2001; van Raden et al., accepted), as well as in tree ring records (e.g. Friedrich et al., 1999; Friedrich et al., 2001) all over the North Atlantic region. However, relative little is know about the internal structure of these minor cold oscillations.
The amphi-Atlantic distribution of these climate events strongly suggests that both, the major and minor climate shifts, likely originate from the North Atlantic and that the climatic signals were transmitted through the atmosphere (e.g. Yu and Eicher, 2001; Denton et al., 2010). Thornalley et al. (2010) observed that the onsets of numerous cold events such as the Aegelsee and Gerzensee Oscillation (GI-1d and b) and the Younger Dryas (GS-1) coincide with meltwater events in the North Atlantic supporting a connection between these abrupt climate changes and meltwater input. They suggest that warming lead to an increased meltwater flux to the northern North Atlantic, which in turn induced abrupt cooling, a cessation in meltwater input, and eventual climate recovery. This implies that feedback between climate and meltwater input produced a highly variable climate, especially during deglaciation terminations. In accordance with this described mechanism, several models suggest that probably all cooling events in the lateglacial period may be due to increased freshwater forcing that inhibited the strength of the North Atlantic heat conveyor (Thornalley et al., 2011). Increased 231Pa/230Th ratios from the Atlantic (McManus et al., 2004) also suggest that the meridional overturning in the North Atlantic was nearly eliminated during the colder phases of the deglacial period as a result of increased meltwater input confirming the significance of variations of the thermohaline circulation (THC) for abrupt climate changes.

Here we present a detailed elemental study on the iconic Lake Gerzensee sediment record (e.g. Siegenthaler et al., 1984) in an unprecedented resolution. We investigated the temporal succession of different elements tied to a robust oxygen isotope stratigraphy. The results are compared in detail with other records in central Europe and the North Atlantic region, which helping to understand the explicit forcings and feedbacks within the lake system, the catchment environment, and the whole Central European climate system in times of abrupt climate change.
4.2. Oxygen isotopes used as lateglacial chronological framework and indicator of climate change

The lacustrine sediments of the Swiss Plateau have long been recognized as excellent archives for studying lateglacial environment and climate (Lotter et al., 1992; Wick, 2000). The lateglacial period has been intensively investigated at Gerzensee often with focus on biotic responses to rapid climatic changes around the Younger Dryas (Lotter et al., 1992; Ammann et al., 2000 and references therein; Magny, 2001) and the onset of the Bølling (Lotter et al., 2012; Magny, in press). These studies demonstrate that at the major climatic shifts at the onsets of the Bølling/Allerød, the Younger Dryas and the Holocene hardly any biotic lags occurred within a sampling resolution of 1-5 decades.

Previous studies have also investigated the stable isotopic composition of Gerzensee lake marl in detail (Eicher and Siegenthaler, 1976; Siegenthaler and Eicher, 1986; Schwander et al., 2000; von Graevenstein et al., 2000; van Raden et al., accepted; von Graevenstein et al., subm.). It has been shown that the fine-grained carbonate matrix is composed of a mix of authigenic calcite and disaggregated calcite encrustations (von Graevenstein et al., 2000; van Raden et al., accepted). This calcite inorganically precipitates in late spring/early summer in the epilimnion due to changes in lake water chemistry (increased temperature, algal activity, and pH) and as an extracellular by-product during photosynthesis e.g. on Characeae and other micro- and macrophytes (von Graevenstein et al., 2000). The δ18O of inorganic carbonates in small/medium open lakes such as Gerzensee mainly reflect δ18O of the lake water during calcite precipitation (Teranes et al., 1999; Ito, 2001; Leng and Marshall, 2004). The δ18O of the lake water seems to be directly related to long-term changes in δ18O of the precipitation in the catchment, mainly representing mean annual air temperatures in the area (Eicher and Siegenthaler, 1976; Schwander et al., 2000). Thus, the δ18O of the inorganic calcite can be used as a proxy for annual air temperature change in the region around Gerzensee (Lotter et al., 2000; von Graevenstein et al., 2000; Schmid, 2011; Lotter et al., 2012).
The signature of the $\delta^{18}O$ record at Gerzensee correlates well with the $\delta^{18}O$ record of the Greenland ice cores, which reflects temperature change in Greenland (Siegenthaler et al., 1984; Siegenthaler and Eicher, 1986; Björck et al., 1998; Schwander et al., 2000; von Grafenstein et al., 2000; van Raden et al., accepted) (Fig. 1). This indicates that the change in mean annual air temperature at Gerzensee is related to temperature changes in Greenland and the changes in both regions are linked by a common cause (Siegenthaler et al., 1984; Siegenthaler and Eicher, 1986; Schwander et al., 2000; von Grafenstein et al., 2000; van Raden et al., accepted). Remarkably, lateglacial cold phases of different duration and amplitude are all well reflected in climate archives over wide regions (e.g. Gerzensee, Mondsee, Ammersee, Greenland, Fig. 1) (Yu and Eicher, 1998; von Grafenstein et al., 1999; Lauterbach et al., 2011). This leads to the basic assumption that the warming and cooling during the lateglacial were hemispheric and that its recording in the oxygen isotopes of the two distant archives of Greenland ice and Gerzensee lake marl was synchronous and without delays (Schwander et al., 2000; von Grafenstein et al., 2000; Lea et al., 2003; Thornalley et al., 2011). Quasi-simultaneous occurrence of major changes is indeed likely since the climatic conditions in Greenland and on the European continent are synoptically dependent, e.g. by the North Atlantic Oscillation (Hurrell et al., 2003). Also, a mechanism that would lead to a very similar, but time-shifted climate pattern at different geographical sites, is unlikely since a climate pattern delayed by more than the synoptic time scale would be dampened and altered, which cannot be observed in the proxy records (Fig. 1).

This assumption of synchronicity can be used to identify and correlate the transitions between the Oldest Dryas (OD), the Bølling/Allerød (B/A), the Younger Dryas (YD), and the Holocene as well as minor oscillations during the B/A in the Gerzensee record (Fig. 1). Consequently, the lateglacial climate shifts reflected in $\delta^{18}O$ fluctuations in the North Atlantic region could be used as time markers (van Raden et al., accepted). This approach was applied for transferring the GICC05 time scale on the new high-resolution Gerzensee record (Fig. 1). This was achieved by using nine tie-points between the 20-yr averaged NGRIP (Rasmussen et al., 2008) and the Gerzensee $\delta^{18}O$ record (Fig. 1). The occurrence of the Laacher See Tephra further constrains the age-
Fig 1. a) Sedimentation rate and δ¹⁸O of bulk carbonate (core GEM) at Gerzensee on depth scale; b) δ¹⁸O records on individual chronologies: Gerzensee (this study); NGRIP ice cores (Rasmussen et al., 2006); Mondsee ostracods (Lauterbach et al., 2011); Ammersee ostracods (von Grafenstein et al., 1999). Dashed lines indicate correlation of identical isotope features (see also Lauterbach et al., 2011); small numbers and squares show tie-points used in this study for establishing the Gerzensee chronology by correlation to the NGRIP record (see van Raden et al. (accepted) for further details).
depth model. Sample ages between the tie-points were interpolated linearly. For better comparison to other terrestrial records the GICC05 scale was converted from originally b2k (before 2000 AD) to BP (before 1950 AD). The resulting sedimentation rates vary between ~6 and ~3.5 cm/100 years with lowest values during the Bølling and highest values during the early Allerød (Fig. 1a). This implies a sample resolution of the elemental record between 3.3 and 5.6 years.

At Gerzensee a radiocarbon-based chronology was not possible due to the absence of terrestrial macrofossils in the studied core sections. In addition, precise conventional radiocarbon dating would be difficult due to a plateau of constant radiocarbon ages during the early part of the Bølling (Ammann and Lotter, 1989; Reimer et al., 2009), which impedes a precise age assignment by $^{14}$C-dating.

We are aware of the dangers of circular reasoning and possible unrecognized chronological uncertainties and the subsequent problems of interpreting the timing and rates of climate change e.g. resulting from a chronology established by wiggle matching distant archives (Blaauw, 2012). Nevertheless, the established age-depth model is well suitable to study the temporal succession and characteristics of events and transitions within the Gerzensee record and its counterparts found in other records.

### 4.3. Study site

Lake Gerzensee is a small kettle-hole lake on the Swiss Plateau at 606 m asl ($46°49'56.95''$N, $7°33'00.63''$E) (Fig. 2). The lake is situated on a ridge, which is dividing the valleys of the Aare and the Gürbe rivers. The rather small catchment of 2.6 km$^2$ (Lotter et al., 1992; Lotter et al., 2000) comprises till of the Aare glacier covering Miocene Molasse sandstone. Its low surrounding relief protected the lake from larger erosional input.

Today, the lake has a small artificial inflow from the North, a small outflow in the South, a lake surface of 25.16 ha and a maximum water depth of 10.7 m. The
surroundings of Gerzensee became ice-free about 17-18 kyr ago (Preusser, 2004; Ivy-Ochs et al., 2008).

Since the water level was higher during the lateglacial than today (Eicher, 1979), shallow water carbonates are found underneath about 1 m of soil in today’s reed zone. This lateglacial marl formed a littoral subaquatic terrace and comprises mainly authigenic carbonates (both, inorganically precipitated and bio-induced) with some molluscan shell debris, but very little organic matter and detrital material. The analyzed sediment core GEM of this high-resolution study was recovered with an UWITEC piston corer at the eastern shoreline (Swiss coordinates: 608 432/186 638) (Fig. 2). This core GEM could be well correlated to previous cores (GEJK, GEA, GE III) from about the same location mainly by the identification of the Laacher See Tephra (LST), δ18O and pollen percentages (van Raden et al., accepted).

4.4. Methods

4.4.1. Stable isotope analysis

The sediment was sampled for continuous stable isotope analyses in core GEM in 5 mm resolution. The sampled material was freeze-dried and shell debris was carefully
removed from the sediment before analysis to minimize biogenic calcite contribution in order to obtain the isotope signal of the inorganic calcite. Carbon and oxygen isotopic compositions are reported in the conventional delta notation ($\delta^{18}$O and $\delta^{13}$C) with respect to VPDB. Analyses were performed in the stable isotope laboratory of the ETH Zurich using a Thermo Fisher Scientific GasBench II coupled to a Delta V mass spectrometer. About 350 $\mu$g of powdered sample material were placed in 12 ml vacutainers, flushed with helium and were reacted with 5 drops of 104 % phosphoric acid at 72 °C. The instrument was calibrated with the international reference materials NBS 19 ($\delta^{13}$C = +1.95 ‰, $\delta^{18}$O = -2.2 ‰) and NBS 18 ($\delta^{13}$C = -5.05 ‰, $\delta^{18}$O = -23.1 ‰). The analytical reproducibility based on repeated measurement of an internal standard was better than ±0.08 ‰.

### 4.4.2. XRF core scanning

The elemental composition of the Gerzensee sediment was semi-quantitatively determined using an Avaatech X-ray fluorescence (XRF) core scanner at ETH Zurich. For detailed technical description see Richter et al. (2006). Continuous stepwise analyses were accomplished over an area of 12 mm cross-core and 2 mm down-core per measurement. Each measurement was performed for 20 sec using a voltage of 10 kV and 30 kV and current of 700 $\mu$A and 1500 $\mu$A, respectively. XRF-analyses result in total counts per measured area for each element (XRF cts). In this study Al, Si, K, Ti, Fe, Rb and Zr are presented, which mainly reflect variations in the individual concentration in the sediment.

### 4.4.3. Biogenic silica (bSi)

Biogenic silica (bSi) was determined using the single-step wet-alkaline leaching method by Ohlendorf and Sturm (2008). We used the same subsamples in 0.5 cm resolution as for the stable isotope analyses in order to avoid any stratigraphic bias between the bSi and $\delta^{18}$O records. About 50 mg of freeze-dried sediment and 10 ml of 1M NaOH were added into a Teflon crucible and heated to 90°C for 3 hours. After this
reaction the content was centrifuged for 10 minutes at 4000/min. 0.05 ml of the resulting liquid were diluted with 10 ml of 0.15M HNO₃ for inductively-coupled plasma, optical-emission spectroscopy (ICP-OES). Simultaneous determination of sodium as an internal standard for volume calibration and aluminum in the leachate allowed correcting (1:2 for Al:Si) for Si derived from silicate mineral dissolution (Ohlendorf and Sturm, 2008). Final results are reported as weight percent.

4.4.4. Pollen analysis

Pollen analyses were carried out on part of core GEM between 13,750 and 14,600 yr BP using freeze-dried samples (0.5 cm³) in 0.5 cm resolution. The samples were treated by standard methods, including HCl, HF, and acetolysis. Pollen concentrations were counted and pollen percentages calculated based on the sum of non-arboreal pollen (NAP). Already existing pollen profiles from parallel Gerzensee cores GEA, GEJK, and GE III were synchronized with the GEM core through detailed correlation of marker horizons and pollen signatures (van Raden et al., accepted). Results of cores GEA, GEJK, GE III are discussed in the works of Eicher and Siegenthaler (1976), Lotter et al. (1992), Wick (2000), Ammann et al. (subm.) and van Raden et al. (accepted).

4.5. Termination 1 at Lake Gerzensee

Fig. 3 shows the stable isotope record together with the XRF elemental measurements and pollen concentration of the Gerzensee sediment over Termination 1. During the OD the detrital influx is high and decreases at the onset of and during the early part the B/A reaching lowest concentration at the GI-1c2 oscillation. The detrital elements stay low during the later Allerød and the Holocene, but show increased values during the YD. Si and Fe values generally follow this overall trend, but additionally hold further information about lake productivity and changes in redox conditions (see chapter 5.2 and 5.3 for detailed discussion). The pollen assemblage at Gerzensee shows a clear change in vegetation cover from a dominance of grasses and herbs during the OD to about only 10 % NAP during the early Bølling.
the Allerød and the Holocene (Fig. 3e). The development to a wide spread of woodland (stable pine forest (Fig. 3f)) took about 750 years after the onset of the Bølling. The YD only shows a minor change towards a more open vegetation cover with slightly more NAP.

![Graph showing high-resolution record of Termination 1 at Gerzensee](image)

**Fig. 3.** High-resolution record of Termination 1 at Gerzensee. a) $\delta^{18}O$; b) sum of XRF counts representing detrital input (Al, K, Zr, Rb, Ti); c) Si XRF counts (line) and discrete biogenic silica measurements (dots); d) Fe XRF counts; e) non-arboreal pollen (NAP) percentages; f) pinus percentages; g) $\delta^{13}C$. Note that XRF results are plotted on logarithmic scales. Color code for the different pollen records from Gerzensee in e) and f): green = GEA, black = GEJK, pink = GEA, yellow = GEM; LST = Laachersee tephra. Blue-shaded areas indicate cold climate phases.
4.5.1. Variation in erosion rates reflected in detrital input

In general, clastic influx, as represented by the sum of the detrital and redox-insensitive elements Al, K, Zr, Rb and Ti, may be transported into a lake either by water or wind. Detrital material deposited during wet events, e.g. heavy precipitation, usually results in distinct turbidite layers in the deepest basin (e.g. Gilli et al., 2013). In contrast, windblown dust material usually is evenly distributed in the lake without strong focusing effects. Aeolian sediment transport into a lake depends on (1) the availability of loose dry material, (2) wind speed and wind direction, which is also strongly modulated by the local landscape surface roughness around the lake, and (3) atmospheric moisture and precipitation during transportation pathway. For all these factors vegetation may play a major role. Changes in vegetation cover influence the stability of soils and minerogenic material in the catchment and potential other source regions and thus the sediment availability. It also modulates how much of the total precipitation can be stored and how much leads to surface runoff since plants and developed soils can uptake and store more moisture than hard rock or undeveloped surfaces (Roos-Barraclough et al., 2004). In addition, the shielding-effect by dense vegetation in the close catchment may circumvent most of the windblown material to reach the lake (Stevens et al., 2000).

At Gerzensee, the amount of detrital elements shows a similar trend as the NAP concentration (Fig. 3), which is in accordance with the expected mechanisms that an increase in forest vegetation is strongly related to a decrease in detrital input. In the Gerzensee record, the decrease of the detrital input ends at the GI-1c2 cold oscillation coinciding precisely with the full-developed and stable forest seen in the NAP minimum (Fig. 3). Therefore, there is a clear relationship between vegetation cover and erosional input through wind and/or water at Gerzensee. Additionally, remobilization processes of detrital material derived from the shore area could have influenced the coring site to some extent.

A comparable study at Mondsee, Austria, (Lauterbach et al., 2011) allows exploring the same linkages between erosive input and forest development in great detail. At Mondsee a very similar erosional input pattern can be observed with a general decrease in aluminum concentration in the early B/A. The detrital input also
stabilizes at the beginning of the GI-1c2 cold oscillation, which is synchronous with the minimum of NAP at that location and the end of the detrital input decrease at Gerzensee. A third example showing a very similar succession of events between detrital influx and NAP pollen evolution was documented in the Lake Lednica record from Poland (Apolinarska and Hammarlund, 2009) although the lower resolution does not allow a detailed temporal comparison with the Gerzensee and the Mondsee record.

All these observations in the B/A suggest that vegetation cover, especially a dense stable pine forest, likely reduces the sensitivity of the catchment to erosion processes and increases the shielding effect resulting in a lower detrital influx over longer timescales. But on decadal and centennial timescales, it seems that the relationship between vegetation cover and detrital influx is more complex. This can be seen in the different detrital signatures over the minor cold oscillations during the B/A at Gerzensee and Mondsee. However, a direct comparison between the two sites is difficult, as the Mondsee record is likely more sensitive to flood events due to its deep-water coring location.

4.5.2. Variations in lake productivity reflected in biogenic silica

Whenever differences occur between the Si signature and the detrital signature, changes in the amount of biogenic silica (bSi) production in the lake may play a role. The deposition of bSi in the sediment is assumed to reflect lake productivity over time (Qiu et al., 1993; Nelson et al., 1995; Ragueneau et al., 2000; Swann et al., 2010).

At Gerzensee, the XRF-Si signature diverges from bSi concentrations and correlates with the detrital signature before ∼14.3 kyr (OD and early Bølling), showing that during the deglacial phase the Si signal is dominated by detritic silicates (Fig. 3). After this time, however, there is quite some accordance between the analyzed bSi concentration and XRF-Si record pointing strongly towards a dominant biogenic origin of the XRF-Si signal. The bSi content with maximum concentration of 2 % are low to very low for a lacustrine setting. Interestingly, the warm phases of the B/A and the Holocene show less bSi than the cold phases OD, AO, and YD. Thus, taking the bSi
signal as a proxy for the lake internal productivity at least after 14.3 kyr it becomes clear that it is not primarily controlled by annual mean temperature as reflected in $\delta^{18}$O, but rather by nutrient availability through detrital input.

The effect of increased productivity during colder periods has been described for several lakes and explained by different mechanisms. For Lake Malawi (SE Africa) it was observed that maximum bSi fluxes occur during the dry and windy winter season, when upwelling or mixing induces high algal production (Pilskaln, 2004). At Sacrower See (NE Germany), a rise of bSi, total organic carbon (TOC) and diatom-inferred total phosphorous concentrations indicates more eutrophic conditions during the YD (Kirilova et al., 2009; Enters et al., 2010). This significant phosphorus release from the sediments occurred during prolonged anoxia in times of stronger stratification by longer ice-cover. In contrast, a rapid increase in bSi in the Meerfelder Maar (SW Germany) at the onset of the YD cold phase is interpreted as a consequence of enhanced soil erosion and nutrient supply (Brauer et al., 1999; Litt et al., 2003). This is in accordance with the observations at Gerzensee and due to the shallow nature of Lake Gerzensee, which limits release of phosphorous from the lake sediments, this fertilization by detrital material most likely explains the bSi variation in Gerzensee.

A way to further monitor past lake productivity could be the analysis of stable carbon isotopes (Fig. 3g). Carbon isotopes in lacustrine carbonates are dependent on the $\delta^{13}$C of the total dissolved inorganic carbon in the lake water which itself is controlled by the isotope composition of the inflowing water, CO$_2$ atmosphere water exchange, and photosynthesis/respiration processes within the lake (Leng and Marshall, 2004). However, in Gerzensee the variable contribution of Chara-derived carbonates, which strongly fractionates the $\delta^{13}$C of up to 5‰ (Ito, 2001; Pelechaty et al., 2010) hinders an unambiguous interpretation of the $\delta^{13}$C record.
4.5.3. Variations in redox conditions reflected in iron variability

Whenever differences occur between the Fe signature and the detrital signature, redox-conditions may play a role. In general, reducing waters have a high soluble content of Fe(II) which, under certain conditions, can subsequently be incorporated into minerals such as pyrite. The most solid iron phases, however, form as iron-oxy-hydroxides containing Fe(III) under oxic conditions (Davison, 1993). Thus, variation in Fe might arise from changes in the position of the redox-boundary. The redox-boundary can be either within the water column, at the sediment water interface, or within the sediment. In geochemical and paleolimnological studies it is sometimes ignored that even in locations with an oxic sediment/water interfaces the pore water of the sediment naturally becomes anoxic in a certain depth of several mm to cm below sediment surface (Kasten et al., 2003). The depth of the redox-boundary is mostly determined by the oxygen saturation of the water and the organic material, which uses O₂ for degradation. In cases when the redox-boundary is at or below the water-sediment interface, a subsurface iron enrichment may be observed (Kasten et al., 2003), caused by upward diffusion of pore water enriched in Fe(II), and its oxidation and fixation in the top oxic sediment layers to an Fe(III) solid phase (Fortin et al., 1993). If sedimentation rate and redox-conditions are stable (steady-state), this redox-boundary stays at about the same sediment depth relative to the sediment surface and the Fe enrichment moves equivalent to this front. However, if the system is in “non-steady state”, the redox-boundary might change its relative depth. Whenever the redox-boundary stays at the same sediment location for a longer period, then iron-oxy-hydroxides may accumulate. This enrichment can be preserved, when the system changes again and the dilution process of the Fe-oxy-hydroxides is slower than the sedimentation rate. Then, a Fe-peak is preserved in the sediment at the location where the redox boundary used to be (Kasten et al., 2003). Later, these enriched iron-oxy-hydroxides can diagenetically change to pyrite under anoxic conditions with ongoing sedimentation. An unsteady-state situation potentially leading to local Fe-enrichments may occur, when (1) the lake level drops, (2) mixing of the water column intensifies (e.g. due to more wind strength and/or exposure), (3) sedimentation rates decrease, (4) organic content decreases, (5) grain size increases, or (6) bioturbation increases or compaction decreases. Thus, peaks in Fe not
coinciding with the overall detrital signature may give hints towards any of those environmental or sedimentological changes.

Comparing the iron content with the detritic input at Gerzensee, some differences can be observed, leading to the conclusion that changes in redox conditions are responsible for the Fe peaks. However, anoxic conditions at the sediment-water interface can be excluded, since the Gerzensee sediments were deposited in shallow water near the paleo-shoreline in ~1-2 m water depth, (M. Magny, unpublished data) and the TOC is rather low. Significant changes in TOC, grain size, or bioturbation in the shallow water sediment deposited during the lateglacial could not be observed. The age model shows some variability (Fig. 1a), but cannot resolve decadal to centennial scale sedimentation rate changes. However, there is no sign for strong short-term changes in sedimentation rate as seen e.g. by accumulation rates of pollen (Wick, 2000; van Raden et al., accepted). Thus, the most likely mechanism leading to non-steady state in the Gerzensee sediment seem to be either (1) a change in lake level or (2) intensified mixing in the water column. At Gerzensee, the most prominent Fe steps and peaks e.g. the onset of the AO, the YD, and Holocene are about 3-5 cm below the proxies for lakelevel lowering (Magny, 2001; Magny, in press) but also especially in times where more wind strength and exposure can be expected. Therefore, both mechanism, either separately or combined, are expected to be responsible for the Fe pattern at Gerzensee.

4.6. Major transitions during Termination 1

4.6.1 Onset of the Bølling

At the transition from the OD to the Bølling period (Fig. 4d), a strong increase over ~3 %o in δ18O can be observed between ~14,680-14,580 yr coinciding with an estimated July temperature increase of 2.5 to 4.5°C (Lotter et al., 2012). At this time, the lake marl at Gerzensee is still influenced by some detrital sediments with insoluble residue of about 40 % derived from Molasse and moraine material (Ruch, 2001; Ammann et al, subm.). This is clearly imaged in the high counts of detrital
elements (Fig. 3b). The detrital contribution (detrital input, Fe, and Si) into the lake system continuously decreases down to <10 % (Ruch, 2001) over a long-term phase from the OD into the B/A. However, this trend is accentuated by several peaks in detrital input, which correlate with peaks in Si and Fe. Near synchronous to the δ¹⁸O shift a strong afforestation can be deduced from palynological analyses by a strong decrease in NAP concentration over a <100 years time period (Lotter et al., 1992; Ammann et al., subm.) (Fig. 3 and 4d).

Steffensen et al. (2008) concluded from their high-resolution Greenland record that most of the temperature change at the onset of the Bølling warm period happened within less than ten years (Fig. 4d). In contrast, the dust and Ca²⁺ records show a decrease over about 50 years starting slightly before the δ¹⁸O step. This suggests that most of the temperature change occurred rapidly at that time, whereas the dust input reacted more gradual. The δ¹⁸O increase at Gerzensee reveals a similar pattern as the δ¹⁸O in Greenland with an initial stepwise rise followed by a more gradual increase. However, the lower sedimentation rate in our record during this time period (see Fig. 1a) impedes a sharp δ¹⁸O signature at the onset of the OD-B/A transition as observed in the highly resolved Greenland ice core record. The discrepancies in the timing of the B/A onset between the annually resolved δ¹⁸O record of NGRIP (Steffensen et al., 2008) and the Gerzensee record (Fig. 4d) can be explained with a different change-point in the 20-yr-average and the annually resolved δ¹⁸O record from NGRIP (see supplementary figure). Since the Gerzensee chronology was established by a match to the 20-yr-average δ¹⁸O NGRIP record, the B/A onset at Gerzensee occurs about 40 years earlier than proposed by (Steffensen et al., 2008). The Gerzensee detrital input cannot be compared with the NGRIP Ca²⁺ record at the onset of the B/A, because it is dominated by the response to the aftermath of the last glacial with high amount of exposed loose sediment in the catchment, which is subsequently brought into the lake. The decreasing trend can be attributed to vegetation development and soil buildup. Distinct peaks in detrital input on top of this decreasing trend are clustering at the beginning of the Bølling (Fig. 3) and indicate periods of increased hydrological activity or storminess.
**Fig. 4.** High-resolution record of the three major transitions at Gerzensee during Termination 1. a) High-resolution $\delta^{18}O$ record of Gerzensee core GEM. b) – d) show $\delta^{18}O$, XRF counts (sum of detrital elements Al, K, Zr, Rb, Ti; Fe; Si; all with 3pt smooth) and non-arboreal pollen (NAP) in comparison to NGRIP $\delta^{18}O$ and Ca$^{2+}$ (Steffensen et al., 2008) for the onset of the Holocene (b), the onset of the Younger Dryas (c), and for the onset of the Bølling (d). The non-arboreal pollen concentrations are from parallel retrieved Gerzensee core GEA (b, c) and GEJK (d). Pink-shaded areas highlight warm climate phases, blue-shaded areas highlight cold climate phases, and white areas represent major transitions. Pale lines represent general trends and change-points in the datasets, for NGRIP as defined by Steffensen et al. 2008). Dashed line marks the lag of the detrital influx within the $\delta^{18}O$ transitions as discussed in the text. Red line in the NGRIP $\delta^{18}O$ in b) shows the suggested ramp and change-points which differ from the ones suggested by Steffensen et al. (2008).
4.6.2. Onset of the Younger Dryas

The transition into the YD cold period (Figs. 3 and 4c) is well reflected with a 3 ‰ decrease in δ18O starting at ~12,880 yr over a period of about 120 years. Around 40 years after the onset of this δ18O decrease an increase in detrital input, Fe and Si is observed. Synchronous with this abrupt increase a change in vegetation towards fewer trees and more shrubs in the catchment occurs (Ammann et al., 2000; Lotter et al., 2000). This may lead to a first conclusion that here local vegetation change influences the amount of detrital input into a lake. A lag in vegetation to δ18O can also be seen in other lacustrine archives from the Swiss plateau, e.g. Lake Aegelsee, Faulenseemoos, Rotsee (Lotter et al., 1992). This offset in vegetation could either be explained with a threshold effect, meaning the time span until vegetation collapses. Or the vegetation reacts not to the temperature shift alone, but more to another climatic factor e.g. change in precipitation or seasonality (Wick, 2000). Other pollen records from Switzerland, e.g. Lake Leysin (Ammann et al., 2000) or Poland, e.g. Lake Gosciaz (Goslar et al., 1993) describe changes in vegetation and temperature without or hardly any delay at the onset of the YD, which is likely related to a too low sampling resolution.

Although the evolution of the local vegetation seems to influence the detrital input, the intriguing similarity between the detrital influx at Gerzensee and the Ca2+ record from Greenland (Fig. 4c) points towards a common mechanism for both records. Steffensen et al. (2008) determined an offset of 55 years of the Ca2+ to the change in δ18O. This is in accordance with the observed offset in Gerzensee of about 40 years. Steffensen et al. (2008) relate the lag in the Ca2+ record compared to the δ18O shift to an increased drying of the Asian dust-source region making enough particles available for aeolian transport. But the now observed similarity with the detrital input at Gerzensee would rather suggest that a simultaneous increase in wind strength controlled the aeolian flux at both locations. This is in agreement with the recent proposed gustiness hypothesis (McGee et al., 2010), where the amount and strength of wind gusts is the primary driver of dust input on glacial-interglacial cycles and not the aridity of the dust-source areas. An increase of wind strength could also explain the observed Fe peaks in the Gerzensee record at the YD onset, which were
formed during phases of more mixing, leading to more oxygenated sediments resulting in short term non-steady state conditions. The results from Meerfelder Maar support this hypothesis of increased wind strengths, since an abrupt increase in storminess during the autumn to spring seasons from one year to the next at 12,679 yr was observed (Brauer et al., 2008). It is suggested that this shift in wind strength represents an abrupt change in the North Atlantic westerlies towards a stronger and more zonal jet.

4.6.3. Onset of the Holocene

The transition from the YD to the Holocene is well reflected in a δ¹⁸O increase of about 4 ‰ from 11,700-11,580 yr (Fig. 4b). The detrital input reveals a long-term decrease during the YD (Fig. 3), but shows an intensified decrease lagging the δ¹⁸O increase at the Holocene transition by ~60 years. The Si concentration closely follows the detrital input over this transition. Fe shows a strong peak in the middle of the δ¹⁸O transition phase and reached subsequently pre-YD values. A vegetation change towards more trees and shrubs seen by a decrease in NAP closely follows or even slightly precedes the δ¹⁸O shift at the YD–Holocene transition (Lotter et al., 1992; Lotter et al., 2000; Wick, 2000) (Figs. 3 and 4b).

The increase in δ¹⁸O in the Gerzensee record at the onset of the Holocene lasts about 120 years. The response of the sedimentary regime to this warming is clearly delayed by several decades. This is in discrepancy to the interpretation of the highly resolved NGRIP record by Steffensen et al. (2008) claiming a slight lead of the Ca²⁺ in comparison to the δ¹⁸O record. But visually it can be argued that the starting change-point in the Greenland record determined by Steffensen et al. (2008) might be set too late applying the RAMPFIT method (Mudelsee, 2000). In case the change-point is set visually, the change in δ¹⁸O starts about 40 years before the change in Ca²⁺ (see supplementary figure and Fig. 4a). The end of the detrital decrease at Gerzensee is synchronous to the δ¹⁸O shift. The Si closely follows the detrital input indicating, as for the beginning of the YD, that in-lake productivity is not primarily temperature-driven. The only proxy responding without delay to the temperature rise is the
change in vegetation cover towards reforestation, which was documented in earlier studies for Gerzensee (Wick, 2000), Lake Lautrey and other lakes from the Swiss Plateau (Magny et al., 2006), as well as for Mondsee (Lauterbach et al., 2011). This immediate response was possible because pine forests persisted during the YD and, therefore, could react to the Holocene warming with no delay. In general, the environmental changes were smaller during the warming at the onset of the Holocene than during the two previous discussed transitions leading to more subtle changes in the observed proxy records.

4.7. Minor oscillations during the Bølling/Allerød

The relatively warm conditions during the lateglacial interstadial are punctuated by four short negative $\delta^{18}O$ excursions of about 1.5 $\%_o$, named at Gerzensee as GI-1e2, Aegelsee Oscillation (AO), GI-1c2, and Gerzensee Oscillation (GO) (Fig. 3; see also van Raden et al., accepted for detailed discussion). These cold oscillations correlate to the Greenland substages GI-1e2, d, -1c2, and b seen in $\delta^{18}O$ and snow accumulation fluctuations (Alley et al., 1993; Björck et al., 1998; Alley, 2000a, b). They can also be observed in other European lacustrine $\delta^{18}O$ records such as Mondsee (Lauterbach et al., 2011), Ammersee (von Grafenstein et al., 1999), and Lake Hawes Water, Northwestern England (Marshall et al., 2002).

Of the four minor oscillations observed in the isotope record during the B/A, only the AO around 14 kyr is well reflected in the Gerzensee proxy records (Fig. 5b). The succession of events at the AO is distinctly different from that at the major transitions during the lateglacial. The AO starts with a prominent decrease in $\delta^{18}O$ of up to 1.6 $\%_o$, stays low for ~80 years, and then gradually recovers until 13,900 yr BP. Although the onset of the AO is sharply defined by a decrease in $\delta^{18}O$, the detrital input, Fe and Si start to increase at least 40 years before, during a time when $\delta^{18}O$ shows only a very slight decrease towards the AO. Detrital input and Fe have their maxima at the onset of the sharp $\delta^{18}O$ decrease. While Fe and the detrital input stay generally low throughout the later part of the AO, the Si signal peaks in the center of this cold oscillation. Si then decreases and reaches pre-AO values at the termination of the AO.
The vegetation change in the catchment mirrors the Si fluctuation in detail revealing higher NAP concentrations when Si counts are highest (Wick, 2000) (Figs. 3 and 5).

**Fig. 5.** High-resolution record of the Aegelsee Oscillation at Gerzensee. a) Overview about the Bølling/Allerød: δ¹⁸O at Gerzensee (above; core GEM) and ice-rafted debris record from North Atlantic on logarithmic scale on its own chronology (Thornalley et al., 2010). Blue-shaded areas highlight the four cold phases during the Bølling/Allerød warm period. b) δ¹⁸O, detrital input (sum of detrital elements Al, K, Zr, Rb, Ti in 3pt smooth), Si XRF counts (line) and discrete biogenic silica measurements (dots), Fe XRF counts and non-arboreal pollen (NAP) from core GEM during the Aegelsee Oscillation. Dashed line marks the lead of the detrital influx and bSi to the sharp δ¹⁸O transition as discussed in the text. c) NGRIP δ¹⁸O and Ca²⁺ (20-yr resolution) (Rasmussen et al., 2008).
Higher NAP concentrations are associated with a depression in birch pollen abundance (Lotter et al., 1992; Ammann et al., subm.) and a pollen-inferred July temperature reconstruction revealed a decrease of about 1°C (Lotter et al., 2012). The AO occurs at a time when vegetation in the Swiss plateau was still unstable and sensitive to abrupt short-term climate change compared to the later phases with close stable forest.

The increase in detrital input, Fe and Si starting about 40 years earlier than the temperature and vegetation shifts could be explained by a preceding increase in wind strength (gustiness) leading to more mixing, as seen in the Fe-peak, and higher aeolian input into the lake, as seen in the detrital peak. It is rather unlikely than this is the result of local effects, such as opening of the vegetation, less shielding and less stable catchment area start later as seen in the pollen concentrations. The increased detrital input consequently triggered lake productivity as seen in elevated bSi values. For the B/A cold oscillations, an increase in the wind strength and/or dust influx is documented for several archives, e.g. the Greenland ice sheet (Rasmussen et al., 2008) (Fig. 5c), the Mediterranean Sea (Rodrigo-Gamiz et al., 2011), the Netherlands (Hoek and Bohncke, 2002), and in the Cariaco basin in Venezuela (Hughen et al., 1996). However, their too broad resolution permits a detailed picture of the succession of events revealing weather the dust influx also precedes the temperature shift. So far, only the Greenland ice core records would allow for a detailed comparison of the temporal succession between δ¹⁸O and a wind proxy. It shows clearly the need for further highly resolved records in order to understand the detailed characteristics and atmospheric circulation pattern during the AO and other short-term fluctuations.

There are several reasons why the other three minor cold oscillations are not well reflected in the elemental records from Gerzensee. GI-1e2 is a very subtle cold oscillation and in the Gerzensee records resolved only in one stable isotope record (van Raden et al., accepted) and in the lake level reconstruction (Magny, in press). So far, the paleoclimatic literature shows an ambiguous picture whether GI-1e2 was a hemispherical event or not since it cannot be defined clearly in many records (Karpuz and Jansen, 1992; Whittington et al., 1996; Brooks and Birks, 2000; Jones et al., 2002;
Marshall et al., 2002; Yu, 2007; Rasmussen et al., 2008). Likely, the impact of the GI-1e2 oscillation was to small to have an imprint on the sedimentary regime or on the lake system.

The later cooling periods, GI-1c2 and GO, occur during a pine forest–dominated phase and its vegetational effects cannot be seen in the pollen records (Lotter et al., 1992; Ammann et al., subm.). This is in accordance with the Lake Lautrey study (Magny et al., 2006) claiming a decreased sensitivity of the vegetation cover to climate change in the second half of the B/A (i.e. after ~13,700 cal yr BP). Furthermore, the atmospheric changes during these two cold oscillations were probably not as pronounced, i.e. for the GO only 1-0.5°C based on pollen and Cladocera (Lotter et al., 2012) as during the AO. This is also indicated by the ice-rafted debris (IRD) record of Thornalley et al. (2010) showing a major peak during the AO, but only slightly increased values during the two later oscillations (Fig. 5a). In addition, the Greenland dust records (Rasmussen et al., 2008) show explicitly higher influx during the AO compared to the other cold oscillations. All this suggests that the temperature decline during the GO and GI-1c2 was less pronounced and the shift in the climate gradient and change in atmospheric circulation across the Atlantic was not sufficient and abrupt enough to increase the detrital flux into Lake Gerzensee.

4.8. Conclusion

Our results show that vegetation cover, especially a dense stable forest, reduces the sensitivity of the catchment to erosion processes on millennial timescale with the result that less detrital material can be transported into the lake. This can be seen by a long-term decrease in detrital input until the onset of the cold oscillation GI-1c2, where the forest fully established. Interestingly, the onset and termination of the Younger Dryas shows a synchronous lag of the detrital influx signatures to the temperature shift at Gerzensee as well as in Greenland. This suggests that major atmospheric changes lead to periods of increased gustiness, which enabled similar patterns of aeolian transport in various areas of the N-Atlantic region lagging the overall temperature shift.
Out of the four cold oscillations during the Bølling/Allerød, only the Aegelsee Oscillation (GI-1d) exhibits a clear signal in the Gerzensee proxy records probably because the other oscillations represent climate oscillations of smaller magnitude and had thus less impact on the environment. The timing of the different events at Gerzensee during the Aegelsee Oscillation is remarkable different from that of the major transitions, showing a lead of detrital influx to the temperature change. Unfortunately, no highly resolved Greenland ice core records are available so far allowing to unravel the exact processes behind.

The elemental proxy records further revealed increased lake productivity, as represented in the XRF Si counts and bSi measurements, during cold periods, e.g. Aegelsee Oscillation and Younger Dryas. This productivity increase is triggered by increased detrital nutrients, which were transported into the lake. Changes in redox conditions are very subtle in shallow Lake Gerzensee, but are observed during climate transitions expressed as Fe peaks.

4.9. Acknowledgements

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Supplementary Figure - High-resolution record of the three major transitions at Gerzensee and Greenland during Termination 1

- Steffensen et al. 2008 proposed change-points
- tie-points used for establishing the chronology

Ages are on GICC05-timescale calculated to BP (before 1950 AD). Plotted values are at mean age of samples. Pink-shaded areas highlight warm climate phases, blue-shaded areas highlight cold climate phases, and white areas represent major transitions.

A: transition Younger Dryas - Holocene;
   Red arrow marks difference between change-point suggested by Steffensen et al. 2008 (RAMPFIT, (Mudelsee, 2000)) and this study (visual).
B: transition Belling/Allerød - Younger Dryas;
   End-point of the transition is difficult to locate by both, visual and RAMPFIT (Mudelsee, 2000) methods.
C: transition Oldest Dryas - Belling/Allerød;
   an offset between the annual record (Steffensen et al. 2008) and the 20-yr-smooth can be observed.

Top: Gerzensee δ^{18}O; numbers and squares show tie-points used in this study for establishing the Gerzensee chronology by correlation to the NGRIP record (see van Raden et al., accepted, for further details)
Bottom: Comparison of NGRIP data; thin lines shows annual resolution (Steffensen et al. 2006), thick lines show 20 year averages (Rasmussen et al. 2008) (NGRIP_GRIP_GISP2_data_on_GICC05_20y_april2008 released April 6, 2008; and GICC05_NGRIP_GRIP_20y_27nov2006)
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Chapter 4 – Termination 1 at Gerzensee, Switzerland


Chapter 4 – Termination 1 at Gerzensee, Switzerland


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Chapter 5

Holocene record of windiness from Central Europe

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1 in preparation for publication
Abstract

For a better understanding of natural climate variability it is essential to extend our knowledge beyond temperature and precipitation reconstructions and learn more about past atmospheric circulation processes and their consequences. Highly resolved records of windiness – the direct expression of atmospheric circulation and air pressure differences in the lower atmosphere – are therefore of great importance. Large-scale winds (temporal and special) may not only be a result of but also a cause for climate variability on regional or even hemispherical dimension (Wunsch, 2006). Thus, deducing the processes leading to variations in wind stress and to include wind properties such as strength, occurrence, and direction into climate reconstructions is indispensable in order to improve the understanding of different climate scenarios. However, it turned out to be difficult to detect high-resolution continental proxies, which exclusively report changes in wind properties and are independent of variables such as temperature or aridity. In this study, we used a record of increased mixing periods in a lake in Northern Switzerland to resolve the natural variation of windiness during the past 7500 years over Central Europe. We found that the laminated sequences in the lacustrine sediments, which form during times of frequent wind-induced short-term mixing of the water column during overall stratification, are highly enriched in Manganese (Mn). These phases of frequent mixing events coincide with increased windiness in the Mediterranean region, a southern position of the Intertropical Convergence Zone (ITCZ), and overall more meandering meridional atmospheric pathways. These findings demonstrate a common response to changes in the hemispherical circulation patterns over wide areas of the North Atlantic region, which occur preferentially during European/North Atlantic cold periods, such as the Little Ice Age (LIA, ~15th-19th century AD).

5.1. Study site

Lake Burgäschi is a small lake located on the Swiss Plateau with a very restricted catchment, and thus receiving negligible erosional input. The lake consists of two basins with 28 and 31 m maximum water depth, which is quite deep in contrast to the
small surface area of 0.21 km². Therefore, its water column is highly sensitive to wind-induced mixing processes. It has been shown that, although not directly adjoined to the Atlantic ocean, Switzerland is mainly influenced by the North Atlantic Oscillation (NAO) (Beniston and Jungo, 2002), but also by the Arctic Oscillation and the Mediterranean and Scandinavian atmospheric patterns (Beniston et al., 1994). Since these atmospheric phenomena are all connected to the Westerlies wind strength and position, the Swiss Plateau, and hence Lake Burgäschisee, is an ideal area to detect atmospheric pathways reaching Europe’s interiors and the reconstruction of the nature of the Westerlies flow.

5.2. Manganese-rich sediments in Lake Burgäschisee

In this study, we focus on a composite core from the deepest basin of Lake Burgäschisee, covering the last 7500 years. The Holocene sediments of Burgäschisee consist of alternating intervals of more or less distinctly laminated sediment and sequences of massive homogenous dark-brown gyttja. The laminae couplets consist of two main types of layers (Fig. 1a): (1) dark-brown layers dominated by fine organic matter, low concentrations in Mn, Fe, Ca, and (2) red-orange layers rich in Mn, Fe, and Ca, calcite and rhodochrosite, where the Mn-content increases with the quality of lamination. Authigenic Mn-rich particles such as rhodochrosite were primarily found in these layers, where they mainly occur as secondary overgrowths on inorganic authigenic calcite (Fig. 1b) but also cluster as fine grains within the organic matrix.

The formation of authigenic Mn-rich particles in lakes is related to redox reactions occurring in the water column and the pore water of the sediment (Stevens et al., 2000; Wetzel, 2001). Authigenic manganese mainly derives from Mn-oxides, which form during the mixing of Mn-rich bottom waters and oxygenated surface waters (Davison, 1993). These oxides may buildup in high concentrations at the sediment-water interface when short-term mixing events cause oxic waters reach the lake floor reacts with additional dissolved Mn(II) that diffuses from the anoxic pore water to the sediment surface (Davison, 1993). A stable Mn-rich layer is then preserved in the
sediment under re-established anoxic conditions, if the reducing process is slower than the sedimentation process, hence only partially re-dissolution of the oxides occurs (Stevens et al., 2000). The preservation of a Mn-layer is additionally promoted by sufficient alkalinity, which enables the transformation from Mn-oxides to Mn-carbonates.

In Burgäschisee sediments, the sections with notably increased Mn contain layers of authigenic calcite, which enabled secondary rhodochrosite formation due to the high alkalinity (Fig. 1). The absence of bioturbation in these laminated sequences indicates that oxic conditions leading to Mn-rich laminae prevailed only during short intervals. In contrast, the non-laminated organic-rich sediment was deposited in stable anoxic bottom waters. Under these long-term reducing conditions, too low Mn-concentrations and too low pH prevented the formation and preservation of Mn-oxides and carbonates in the sediment (Stevens et al., 2000).

Fig. 1. Lamination in Lake Burgäschisee sediments; a) Core picture of laminated sediment. Red-orange layer show high Ca and Mn-values, while dark organic-rich layers show low values in XRF core scanning (0.2 mm resolution). Low arbitrary K-signature reflects negligible detrital influx (noise below detection limit). b) NanoSEM image of authigenic calcite with elemental distribution profile (EDX): blue line reflects Mn covering the outer rim of the Ca-rich authigenic calcite (red line).
5.3. Climatic implications

In this context, the presence of Mn at Burgäschisee represents periods of frequent short-term lake mixing while the un-laminated sediments were deposited during long-term stratification. But what caused the observed mixing events? And what does this tell us about past climate variations in Europe?

5.3.1. Long-term trend over the Holocene

In the Burgäschisee record, there is no notable Mn before 6500 years BP, increasing Mn values in the laminated sections of the mid-Holocene, and highest values during lamination in the late Holocene after 4000 years BP (Fig. 2b). The transition towards higher Mn-values is in line with the trend of Neoglacialion in Europe (Matthews, 2007) coinciding with decreasing solar radiation and the establishment of stabilized sea levels and firmly established thermohaline circulation due to negligible meltwater fluxes (Matthews, 2007). As a result, signatures of internal forcings such as thermohaline circulation variability started to overprint external solar-forced signatures (Debret et al., 2009). This enabled also changes in atmospheric circulation to be more prominent in many records such as in Burgäschisee from this time onwards. The topmost sediment is strongly biased by anthropogenic lake level lowerings, which started in the second half of the 19th century (Guthruf et al., 1999) and thus does not express natural wind changes.

In this study, we focus on the centennial and decadal variation above this described larger trend because the large trend is likely caused by the vegetation and soil development in the catchment, which influenced the chemistry of lake water and sediment.
Fig. 2. European proxy records of the past 7500 years; a) The smectite/(illite+chlorite) is are used to reconstruct past storm histories in a coastal lagoon environment at the central part of the Gulf of Lions, Western Mediterranean Sea (Sabatier et al., 2012). Red line represents a 1500 year smooth of the original record (black), b) The Mn content in Burgäschisee sediments reflects periods of frequent short-term mixing events. Fine gray lines show raw data, black line represents 20 year smooth, red line shows 1500 year smooth, c) The Ti flux record in a peat bog in the Jura Mountains of Switzerland reflects atmospheric dust deposition (Thevenon et al., 2012). Black line shows original data, red line 1500 year smooth. Black horizontal bars close to the proxy-records show calibrated radiocarbon ages used for establishing the individual chronologies. LIA=Little Ice Age, MCA=Meditival Climatic Anomaly (red bar), MHWP= Mid Holocene Warm Period. Blue shaded areas reflect periods of frequent short-term-mixing events in Lake Burgäschisee.
For understanding the climatic processes leading to the observed frequent mixing events in Burgäschisee and identifying the larger teleconnections involved, proxies of various regions including other parts of Europe, the tropics, and the high latitudes were compared in detail over different time scales with our record. The distinction whether records represent mean or extreme wind speeds or different season of increased windiness is not crucial on above-decadal time scales since they all seem to be highly correlated. This can be concluded from the investigation of the Twentieth Century Reanalysis (20CR) data (Compo et al., 2011) of the last 140 years (Supplementary Figure 6).

5.3.2. Variability in atmospheric circulation over Europe

On an European scale, we observe over the past 7500 years that the sections of increased Mn-values indicating periods of frequent short-term mixing in Burgäschisee (Fig. 2b) coincide with marine invasions into a lagoon at the French-Mediterranean shoreline caused by storm events (2012) (Fig. 2a) and increased dust influx from the Sahara Desert to a peat bog in the Swiss Jura Mountains (Le Roux et al., 2012) (Fig. 2c). This synchronicity indicates a strong atmospheric link resulting in a common wind signature over wide regions of Central Europe. This link can be seen in frequent cyclone development and a meridional atmospheric circulation in the area in times when the Westerlies wind regime is weak or disrupted (Alpert et al., 2006; Barkan et al., 2005; Littmann and Steinrücke, 1989; Raible et al., 2007; Ulbrich et al., 2012).

For a more detailed picture, we focus on the well-studied period of the last 1500 years that includes the Medieval Climate Anomaly (MCA) and LIA (Fig. 3). These particular periods are clearly visible in Burgäschisee sediments with highly increased Mn-values (Fig. 3a) during a distinctly laminated sediment section of the LIA indicating frequent short-term mixing of the water column. In contrast the MCA is characterized by mainly homogenous dark sediments and only short periods of weak laminations indicating persisting stratification of the water column. This pattern of an increase in windiness during the LIA cold period compared to the MCA warm phase is seen in most European coastal archives (2009). This strong correlation over large
parts of Western Europe is also seen in the 20CR data (Supplementary Figure 5). Our proxy-data (Fig. 2 and 3) indicates that this correlation likely existed throughout the complete mid- and late Holocene.

5.3.3. Hemispherical variability of atmospheric circulation

On a wider spatial scale, there is strong anti-correlation between increased windiness in Central Europe and the number of hurricane landfalls in the tropical Atlantic (Fig. 3). These two areas are atmospherically linked by the Westerlies track, which is strongly related to the position of the ITCZ. A southerly position of the Azores High (AH), the ITCZ and the Westerlies track tends to force storms into the Gulf of Mexico, whereas northerly position allows storms to track up the Atlantic coast (Fraedrich and Müller, 1992; Malaizé et al., 2011; Mann et al., 2009). These two different patterns are seen during the contrasting MCA and LIA periods. During the MCA, frequent hurricane landfalls are associated with reinforcing effects of La Niña-like conditions and relative tropical Atlantic warmth in correspondence with a northerly shift of the ITCZ (Mann et al., 2009). Over the past 140 years the 20CR (Compo et al., 2011) shows that this situation of more hurricane landfalls in the tropics coincides with less winds in western central Europe and can be explained by a strong zonal atmospheric circulation with rather round-shaped and strong AH and IL (Supplementary Figure 7). In contrast the LIA shows less hurricane landfalls due to reinforcing effects of El Niño-like conditions and relative tropical Atlantic cooling in correspondence with a southerly shift of the ITCZ (Mann et al., 2009). This pattern coincides in the past 140 years (Compo et al., 2011) with rather meridional atmospheric circulation and more NE-SW elongated weak AH and IL in times of more windiness in Western Europe (Supplementary Figure 7).

In high latitudes, fluxes of sodium derived from sea salt (ssNa+) (Fig. 3c) and dust (K) in Greenland ice cores were increased during the LIA compared to the MCA. This often has been interpreted as increased atmospheric pressure gradients (Dawson et al., 2003; Meeker and Mayewski, 2002) associated with strong zonal pathways, which contradicts to our observations. However, others (Kreutz et al., 1997) explain the increased ssNa+ by more meridional atmospheric circulation during the LIA. This agrees with studies including modeling and statistical approaches for investigating
the aerosol transport to Greenland in more detail, which propose a splitting of the jet stream pathways during European cold phases on various timescales (Fischer, 2001; Fischer et al., 2007). This would result in a more direct

![Diagram]

**Fig. 3. Hemispherical proxy records of the past 1500 years; a)** The Mn content in Burgäschisee sediments reflects periods of frequent short-term mixing events (blue bars). Fine gray lines show raw data, black line represents 20 year smooth, red line shows 1500 year smooth, **b)** estimates of tropical cyclone activity over the past 1,500 years by using regional sedimentary evidence of landfalling hurricanes, red horizontal line only for visualization (Mann et al., 2009) **c)** ssNa+ analyzed in the GISP2 ice core record from Greenland, red line only for visualization. (Mayewski et al., 1997) **LIA=Little Ice Age, blue shaded areas reflect periods of frequent short-term-mixing events in Lake Burgäschisee.**
transport from Asia over the Pacific to Greenland by the northerly part of the jet. Together with generally more blocking events during European cold phases (Hakkinen et al., 2011), these observations support the scenario of more meridional meandering atmospheric circulation increasing the windiness in Western Europe.

Our data in combination with available proxy data from high and low latitudes in the North Atlantic region suggests zonal atmospheric circulation during the MCA and more meridional circulation during the European cold phase of the LIA (summarized in Fig. 4). These two different patterns are often linked to variation in the NAO. However, existing NAO reconstructions are often contradictory for pre-industrial times since the same NAO index can result from either a stronger AH or a stronger IL, which are related to different influences on the climatic situation (Beniston et al., 1994). Also, the effect of the NAO pattern on climate varies regionally (Hurrell, 1995) due to the high variability of atmospheric pathways during blocking situations. It has been suggested that at long-term timescales the climatic variability in the North Atlantic region cannot be restricted only to changes in NAO but should take into account multiple atmospheric patterns such as the strength of the polar vortex (Walter and Graf, 2005).
Fig. 4. (previous page)
Atmospheric circulation patterns during the Little Ice Age and Medieval Climate Anomaly;
a) During the Medieval Climate Anomaly (MCA) palaeo-records indicate rather zonal atmospheric
circulation, a northward-shift of the atmospheric circulation pattern, and frequent hurricane landfall. b) 
During the Little Ice Age (LIA) palaeo-records indicate more meandering atmospheric circulation
patterns, a southward shift of the Intertropical Convergence Zone (ITCZ).

5.4. Conclusions

Our study demonstrates that the formation of the Mn-rich laminae is related to short-
term mixing events due to variation in wind stress on the lake surface. The Mn-record of Lake Burgäschisee is associated to a suite of records that have been attributed to changes in atmospheric circulation patterns. During the mid- and late Holocene a common picture of increased windiness in Central Europe and the Mediterranean region, and with changes of hurricane tropical landfall frequency was observed. This notable coherency indicates a common response to large-scale atmospheric patterns over wide areas of the North Atlantic region. A detailed study of the LIA/MCA together with the reanalysis data of the past 140 years (Compo et al., 2011) strongly suggests a more meridional and variable circulation pattern during the LIA cold phase. This is in accordance with data of the high and low latitudes over the North Atlantic region. However, caution should be taken in extrapolating a NAO proxy record due to uncertainties in NAO behavior on longer (millennial) time scales (Grumet et al., 2001). For establishing a more complete record of Holocene aeolian activity and teleconnections, additional high-resolution records of windiness with well-established chronologies from continental regions are needed.
5.5. Method Summary

5.5.1. XRF core scanning

X-ray fluorescence (XRF) core scanning using an Avaatech core scanner was performed in continuous 1 mm resolution covering the entire Holocene period. Here, an area of 1mm down-core and 12 mm cross-core for 20 second per measurement was analyzed with both, 10 kV (1500µA, no filter) and 30 kV (2000µA, Pd-thick filter). The laminated section between 150 and 500 years cal BP has been investigated in greater detail in a continuous down-core resolution of 0.2 mm. Here, an area of 0.2 mm down-core and 12 mm cross-core for 20 seconds per measurement was analyzed with both, 10 kV (2000mA, no filter) and 30kV (2000mA, Pd-thick filter). Results are shown in Fig. 1a and Supplementary Figure 1 and 2.

5.5.2. NanoSEM

Electron microscopy together with elemental analyzes of polished sediment-epoxy-blocks were performed at a Nano Scanning Electron Microscope (NanoSEM) including an energy-dispersive X-ray spectrometer (EDX). This was used to reveal the precise composition and relationship of Mn to the other mineral-forming elements (Fig. 1b). Mn-Fe-rich particles and overgrowths can also be observed in SEM images by their bright white color (highly refractive mineral), whereas the calcite grains are rather homogenous and gray (less refractive) (Fig. 1b).

5.5.3. XRD

Mineralogical information was gathered by XRD (powder X-ray diffractometer, Bruker, AXS D8 Advance, equipped with a Lynxeye detector). (Supplementary Figure 3).
5.6. Acknowledgements

The project has financially been supported by an ETH research grant CHIRP1 (CH1-02-08-2), which is gratefully acknowledged. The authors thank anyone who was assisting in the field and the lab, and Harald Sodemann for constructive comments and discussions on the manuscript.

5.7. Supplementary information

S1. Material

In summer 2009 three parallel sediment cores were retrieved from the deepest basin of Lake Burgäschisee (N 47°10’8.5“, E 7°40’5.9“ at 465 m a.s.l.) using an UWITEC piston corer. The coring location was selected based on previous acquired 3.5 kHz seismic data. Although no seismic penetration was observed, a detailed bathymetric map could be created. In this study we focused on a composite core of 8 sections with a total length of 6.5 m, covering the last 7500 years. Past climate and environmental change were inferred from multiple variables, including sedimentology, elemental and mineralogical geochemistry.

Lake Burgäschisee has a very restricted catchment (3.2 km², highest elevation 75 m above lake level) (Guthruf et al., 1999) strongly limiting the detrital influx into the lake. That the detrital input over the majority of the core can be neglected can be seen in the low counts of the detrital elements K, Ti, Rb (Supplementary Figure 1a) which do not not correlate with the Mn-Fe signature (Supplementary Figure 1b). In the section around 2000 yrs BP which shows increased detrital influx, the clear division in detrital layers and Mn-rich layers (Supplementary Figure 2) confirms that the authigenic formation of Mn- and Fe-rich particles is unaffected by erosion processes.

Both, NanoSEM (not shown) and XRF (Supplicantary Figure 1), reveal a high correlation between Mn and Fe. In this manuscript we focus on the distribution of Mn in the sediment, since the general processes in lakes for Mn and Fe are quite similar
with Mn being slightly more sensitive to variations in redox-conditions (Davison, 1993).

XRD was used to get insights of the mineralogical composition of the various layers, clearly indicating the presence of rhodochrosite (MnCO₃) in the sediment.

**Supplementary Figure 1** – XRF data from Lake Burgäschisee showing (a) detrital elements and (b) redox-sensitive elements. The y-axes with different scales represent the concentrations of each element.
Supplementary Figure 2 – Lamination with detrital layers at ~2000 BP highlights the correlation of Mn and Ca and the occurrence of sporadic detrital-rich layers represented by Ti. The y-axes with different scales represent the concentrations of each element.

Supplementary Figure 3 – XRD results showing a typical spectrum of a rhodochrosite-rich layer after removal of organic matter.
S2. Chronology

The age-depth model (Supplementary Figure 4) is based on eight 14C ages of terrestrial plant remains (Supplementary Table 1) and was developed using OxCal 4.1.7 calibration program and the INTCAL09 calibration set (Bronk Ramsey, 2008; Bronk Ramsey et al., 2010; Reimer et al., 2009). The mean of the 2 sigma range of each date was used for the age points of the chronology. During the well-laminated LIA period, varve counting was performed and included in the age-depth model. In two countings (1x forward and 1x backward) a number of 380 and 355 lighter (summer) layers have been observed and the second varve count was included into the age-model (difference to first count ~8%). The floating varve counts were anchored to the radiocarbon chronology by using the topmost 14C-date, which was sampled near the base of the LIA laminated sequence (showing 338 laminae on top of this radiocarbon date). The constructed age-depth model results in sedimentation rates of 25 cm/100 years in the top section decreasing continuously to 4 cm/100 years at the bottom (due to compaction and decreased water content). All data are reported as calibrated calendar years BP (before 1950 AD).

Supplementary Figure 4 - Age-depth model Burgäschisee showing 14C-ages (red dots) and counted layers (black squares). Two slumps (blue circles) of 7.5 and 8 cm thickness were identified and excluded from the age-depth model.
**Supplementary Table 1.** \(^{14}\text{C} \) ages from the Burgäschiisee record

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Core Section</th>
<th>Section Depth</th>
<th>Composite Depth</th>
<th>14C age BP</th>
<th>±</th>
<th>INTCAL 09 up 2sig</th>
<th>low 2sig</th>
<th>av. 2sig</th>
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<tr>
<td>ETH-43940</td>
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<td>154</td>
<td>445</td>
<td>25</td>
<td>531</td>
<td>477</td>
<td>504</td>
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<tr>
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<td>72.5-73.5</td>
<td>267-268</td>
<td>1340</td>
<td>25</td>
<td>1305</td>
<td>1184</td>
<td>1244.5</td>
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<tr>
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<td>23-26</td>
<td>338-341</td>
<td>2145</td>
<td>30</td>
<td>2304</td>
<td>2006</td>
<td>2155</td>
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<tr>
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<td>ETH-43947</td>
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<td>ETH-43948</td>
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<td>78-81</td>
<td>670-673</td>
<td>9565</td>
<td>35</td>
<td>11090</td>
<td>10738</td>
<td>10914</td>
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<tr>
<td>*1)</td>
<td>below LST (BurgC7-8)</td>
<td>66.5</td>
<td>758.5</td>
<td>10760</td>
<td>105</td>
<td>12921</td>
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<td>16327</td>
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<td>15739.5</td>
</tr>
</tbody>
</table>

All material dated were plant macrofossils. \(^{14}\text{C} \) ages are calibrated using OxCal v4.1.7 and INTCAL09 (Reimer et al., 2009).

*1) from Hajdas et al. (Hajdas et al., 1993)

### S3. Twentieth Century Reanalysis data of the last 140 years

The supplementary figures 5-7 are based on the Twentieth Century Reanalysis (20CR) Version 2 (Compo et al., 2011) using the ensemble mean analysis. The 20CR dataset provides an estimate of global tropospheric variability, and of the dataset’s time-varying quality, from 1871 to the present at 6-hourly temporal and 2° spatial resolutions (Compo et al., 2011).
Supplementary Figure 5: Correlation between decadal means of wind speed at the lowest model level (0.995 sigma) at all grid points with wind at the grid point closest to Burgäschisee (48° N, 8° E). The left plot uses decadal mean wind speed at Burgäschisee, the right plot uses the decadal average of the ensemble median of the annual 98th percentile of six-hourly wind at Burgäschisee. All decadal means have been linearly detrended. Only correlations that are significant at the 90% level ($n = 14$) are shown.

Supplementary Figure 6: Correlations between decadal means of seasonal mean wind speed and decadal means wind speed at the lowest model level (0.995 sigma). All decadal means have been linearly detrended.
Supplementary Figure 7: Contours of sea-level pressure (SLP), wind speed at the tropopause and 500 hPa geopotential height (GPH) for the average of seven decades with high wind speeds at the lowest model level (0.995 sigma) at the grid point closest to Burgäschisee (48° N, 8° E) and seven decades with low wind speed. Decadal means of wind speed at Burgäschisee have been linearly detrended before selecting the decades. The bar plots show for the two situations the number of landfalling Atlantic hurricanes according to HURDAT, the average sodium concentration in the GISP2 ice core (1870 to 1988) and the strength of winter storms (i.e., the 98th percentile of the October to March daily maximum wind speed) in Swiss wind measurements from 1891 to 2010.
5.8. References


Chapter 6

Conclusion and outlook
1. Conclusion

The main objective of this thesis was the reconstruction of environmental and climatic variables over the past 15,000 years in high resolution by studying the overall geochemical composition in different Swiss lake sediments. As a basic prerequisite to fulfill this task, robust and detailed chronologies were established for all lake records.

XRF core scanning was applied for analyzing the elemental composition of the lacustrine sediment cores. The resulting continuous high-resolution data sets demonstrate the great use of this modern method. In combination with additional sedimentological and geochemical analyses on selected samples, the XRF data could be set into a mineralogical and sedimentological context. The resulting reconstructions of the catchment and lake histories lead to a better understanding of different physical, biological and geochemical processes in the lake systems and environment.

By comparing the new findings with other archives over the North Atlantic region, the results could be set into a larger context and thus identify possible mechanisms of climate variability from a continental point of view. Eventually, these resulting high-resolution data sets of sedimentological and geochemical parameters can be used as input for climate models.

More specifically the following major conclusions can be drawn from this thesis:

Chapter 3:

• It was possible to refine the late-glacial chronology at Lake Gerzensee by combining four parallel δ¹⁸O records. The resulting stack highlights the occurrence of four minor oscillations during the Bølling/Allerød. A detailed comparison with other records and previous publications illustrates the hemispherical appearance of these events and enabled a detailed correlation and refined terminology of events.
• The improved Gerzensee chronology and the high-resolution $\delta^{18}O$ stack were used as a basis for several detailed environmental interpretations at Gerzensee and further has the potential to serve as an important new reference curve of late-glacial climate for Central Europe.

Chapter 4:

• High-resolution XRF core scanning and stable isotope analyses on the sediment record from Lake Gerzensee illustrate the detailed pattern of climatic changes over Termination 1. Together with previously published proxy records this data demonstrates the event successions in the environment and lake system regarding detrital influx, in-lake productivity and redox conditions.

• Detrital input in Lake Gerzensee is reflected by the sum of the elements Al, K, Zr, Rb and Ti and shows a decreasing trend during the early part of the Bølling/Allerød until 13 600 yr BP. This coincides with the full establishment of stable pine forest in the vicinity of the lake and documents the strong linkage between local vegetation and erosional input.

• The highly resolved records from Gerzensee sediments and Greenland ice cores reveal eminent similar patterns at the onset and termination of the Younger Dryas at which the detrital input lags the temperature change by several decades. These similarities in dust proxies suggest that changes of large-scale atmospheric circulation patterns and variation in gustiness likely dominated the aeolian flux over the larger North Atlantic region.

• At the Aegelsee Oscillation (GI-1d), the detrital input in Gerzensee leads the $\delta^{18}O$ decrease, which is so far not documented for the Greenland ice core records. The three further cold oscillations during the Bølling/Allerød were either too weak or the environment was too stable so that no impact on the elemental record of Gerzensee could be observed.

Chapter 5:

• In Lake Burgäschisee the laminated sediment sequences are highly enriched in Manganese compared to the non-laminated sections. Geochemical analyses revealed that Mn-rich particles such as rhodochrosite are primarily found in
distinct layers, where they mainly occur as secondary overgrowths on inorganic authigenic calcite.

- In Lake Burgäschisee the formation of the Mn-rich laminae is related to short-term mixing events due to variation in wind stress on the lake surface and thus to changes in atmospheric circulation pattern. A detailed comparison of records from high and low latitudes and Central Europe during the past 1500 years suggests increased windiness in Northern Switzerland during times of more meridional atmospheric circulation over the Northern hemisphere during European cold periods such as the Little Ice Age.

**XRF core scanning on lake sediments in general:**

- XRF core scanning helps to identify changes in lake water chemistry and redox processes. For example, while Al, Rb, Ti, and Zr are not sensitive to redox-conditions and derive only from detrital material, the amount of Mn and Fe may change with differences in the redox conditions of the lake water and sediment.

- The type of lake system influences the elemental composition of the lake sediment, i.e. different concentrations of authigenic calcite (seen in Ca), detrital influx (Al, K, Rb, Ti, Zr), or redox-sensitive elements (Mn, Fe) are strongly dependent on a complex combination of lake properties such as trophic state, depth-to-surface ratio, inflow, catchment structure and vegetation cover.

- All studied lake records show distinct changes in sedimentation characteristics at the onsets of the B/A, YD, and Holocene. Another change at about 7000 years occurs when climate changed from being dominated by solar and oceanographic changes, whereas later by atmospheric variations (Debret et al., 2009). At ~4000 BP the neoglaciatic phase (Matthews, 2007) has a strong impact on the environment shown in all studied records. From ~2000 years BP onwards human impact can bias the natural evolution of the lake systems in the Swiss Plateau.
2. Outlook

In addition to the new insights in methodological, sedimentological and paleoclimatological aspects, new questions emerged calling for further research. For establishing a more complete understanding of climatic variability in the past and the involved teleconnections, comparisons of environmental evolution over climatic transitions over larger regions and timescales is required. Therefore, additional high-resolution records from continental regions with well-established chronologies are of urgent need. More specifically, the following issues strongly suggest additional studies concerning:

**XRF core scanning method:**

- XRF core scanning has evolved to a widely-used, fast, relatively easy and cheap to apply, non-destructive technique for producing high-resolution records of elemental composition in sediment cores. However, there is still need to refine this method so that detection limits can be lowered, statistical analyses standardized, errors quantified, and secondary effects (such as grain size and water content) better understood. With improving the XRF core scanning technique there is great potential in getting further detailed information about sedimentological signatures, especially redox-conditions, micro-tephra layers and minor particle fluxes such as windblown dust particles.
- So far, it sometimes seems difficult to distinguish the source of detrital material (long-distant transport vs. catchment erosion) by XRF core scanning and to reconstruct the transport mechanism (wind vs. water). Also, the robust detection of different redox-sensitive elements such as Mo, Cr, and V, which all have different redox-potentials, would be an advantage for reconstructing the position and stability of lake stratification. Although this thesis is one step further to understand the wind-induced changes in lake systems, further research in this respect is needed.

**Existing records and archives:**

- The study of laminated sequences of the different lake records needs further attention. It sometimes remains unclear what is leading to laminated and non-
laminated periods (e.g. in Lake Baldegg) and what causes the lamination to faint (e.g. in Lake Soppensee). In addition, different composition of lamination in the YD vs. Holocene could be observed in Lake Soppensee and Burgäschisee, but need further research. Therefore, thin-section analyses would be of great value. Only with thin-sections the question can be solved whether those laminae represent varves or do not represent seasonal sedimentation changes. Eventually, detailed varve analyses and counting in the laminated sequences would give notably new insights into the duration, timing, internal structure, and rates of change of the different climatic situations.

**additional records and study areas:**

- For getting a more detailed and reliable picture of past atmospheric patterns, it is necessary to find more continental archives, which proxies can be interpreted as wind properties preferentially in highest resolution. This is essential for the identification and distinction of different seasonality, frequency, and strength of winds and thus give new insights into the mechanisms influencing wind properties.

- More high-resolution lateglacial archives need to be investigated concerning its minor climatic oscillations. The detailed study of event successions in other regions and archives in comparison to the Gerzensee record will help to understand the climatic situation during the B/A and the mechanisms leading to decadal-scale cold periods. In addition, this might solve the question why the observed event GL-1e2 in the Bølling period has not been clearly identified in many records so far.

- So far, little is known on the influence on mean wind strength in different regions and environments on decadal to centennial time scales. For testing and refining the different proposed atmospheric circulation patterns modeling approaches on different time scales will be of great help. This could clarify the sensitivity of different regions to different wind properties (such as mean wind speed, number of wind gusts, seasonality) and highlight regions most suitable for studying variation of windiness.
3. References


Appendix

A.1. Age models
A.2. XRF data
A.3. Sediment core images
A.1. Age models

A.1.a. Burgäschisee

Tab. 1. \(^{14}C\) ages used for establishing the age model

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Core Section</th>
<th>Section Depth</th>
<th>Composite Depth</th>
<th>(^{14}C) age BP</th>
<th>± 2sig</th>
<th>INTCAL 09</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETH-43940</td>
<td>BurgC1-2</td>
<td>59.5</td>
<td>154</td>
<td>445</td>
<td>25</td>
<td>531</td>
</tr>
<tr>
<td>ETH-43941</td>
<td>BurgC2-3</td>
<td>72.5-73.5</td>
<td>267-268</td>
<td>1340</td>
<td>25</td>
<td>1305</td>
</tr>
<tr>
<td>ETH-43942</td>
<td>BurgC3-4</td>
<td>23-26</td>
<td>338-341</td>
<td>2145</td>
<td>30</td>
<td>2304</td>
</tr>
<tr>
<td>ETH-43943</td>
<td>BurgC4-5</td>
<td>43-45</td>
<td>448-450</td>
<td>3080</td>
<td>25</td>
<td>3367</td>
</tr>
<tr>
<td>ETH-43944</td>
<td>BurgC4-5</td>
<td>93-94</td>
<td>498-499</td>
<td>3675</td>
<td>30</td>
<td>4090</td>
</tr>
<tr>
<td>ETH-43945</td>
<td>BurgC5-6</td>
<td>51-53</td>
<td>556-558</td>
<td>4745</td>
<td>30</td>
<td>5585</td>
</tr>
<tr>
<td>ETH-43946</td>
<td>BurgC5-6</td>
<td>71-73</td>
<td>576-578</td>
<td>5290</td>
<td>35</td>
<td>6184</td>
</tr>
<tr>
<td>ETH-43947</td>
<td>BurgB5-6</td>
<td>84.5-86.5</td>
<td>615-617</td>
<td>6190</td>
<td>35</td>
<td>7240</td>
</tr>
<tr>
<td>ETH-43948</td>
<td>BurgC6-7</td>
<td>78-81</td>
<td>670-673</td>
<td>9565</td>
<td>35</td>
<td>11090</td>
</tr>
<tr>
<td>ETH-43949</td>
<td>BurgC8-9</td>
<td>47.5-53.5</td>
<td>839-845</td>
<td>13015</td>
<td>50</td>
<td>16327</td>
</tr>
</tbody>
</table>

All material dated were plant macrofossils. \(^{14}C\) ages calibrated using OxCal v4.1.7.

Atmospheric data from Reimer et al. (2009).

*1) from Hajdas et al. (1993)

Tab. 2. Sediment Composite Lake Burgäschisee

<table>
<thead>
<tr>
<th>Section Name</th>
<th>Photo length (cm)</th>
<th>used in composite</th>
<th>Composite Depth Bottom (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BurgC 0-1</td>
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<td>0-98.5 cm</td>
<td>98.5</td>
</tr>
<tr>
<td>BurgC 1-2</td>
<td>100.5</td>
<td>0-41.5 cm</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>42.5-48 cm</td>
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<tr>
<td>BurgC 2-3</td>
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<td>0-97.5 cm</td>
<td>293</td>
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<tr>
<td>BurgC 3-4</td>
<td>94.5</td>
<td>67.5-94 cm</td>
<td>319.5</td>
</tr>
<tr>
<td>BurgC 4-5</td>
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<td>4.5-91 cm</td>
<td>406</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12.5-27.7 cm</td>
<td>505</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28.2-100 cm</td>
<td></td>
</tr>
<tr>
<td>BurgC 5-6</td>
<td>100</td>
<td>0-99 cm</td>
<td>604</td>
</tr>
<tr>
<td>BurgC 6-7</td>
<td>101.5</td>
<td>75-90 cm</td>
<td>619</td>
</tr>
<tr>
<td>BurgC 7-8</td>
<td>100</td>
<td>29-100 cm</td>
<td>690</td>
</tr>
<tr>
<td>BurgC 8-9</td>
<td>101</td>
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*1) gaps excluded
Tab. 3. Layer counting

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<th>composite depth</th>
<th>year BP</th>
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<td>0 (surface)</td>
<td>59 (2009 AD)</td>
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<tr>
<td>87.9</td>
<td>166</td>
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<td>90.1</td>
<td>176</td>
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<tr>
<td>91.7</td>
<td>186</td>
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<td>93.4</td>
<td>196</td>
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<td>95</td>
<td>206</td>
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<td>96.7</td>
<td>216</td>
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<td>98.7</td>
<td>226</td>
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<td>100.9</td>
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<td>103.3</td>
<td>246</td>
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<td>105.1</td>
<td>256</td>
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<td>107.7</td>
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<td>119.9</td>
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<td>123.9</td>
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<table>
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<tr>
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<th>year BP</th>
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<tbody>
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<td>145.4</td>
<td>456</td>
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<tr>
<td>145.5 *1)</td>
<td>457</td>
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<tr>
<td>147.3</td>
<td>466</td>
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<tr>
<td>149</td>
<td>476</td>
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<tr>
<td>150.5</td>
<td>486</td>
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<tr>
<td>152.3</td>
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<td>154.3</td>
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<tr>
<td>156.9</td>
<td>516</td>
</tr>
<tr>
<td>155.4</td>
<td>536</td>
</tr>
</tbody>
</table>

*1) two event layers were excluded from the age model

Figure 1: Age-depth model and Sections Burgäschisee
A.1.b. Soppensee

Tab. 1. $^{14}$C-ages for age model in addition to dates from Hajdas et al. (2010).

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Core Section</th>
<th>Section Depth</th>
<th>Mean Composite Depth</th>
<th>$^{14}$C age BP</th>
<th>±</th>
<th>INTCAL 09 up 2sig</th>
<th>low 2sig</th>
<th>av. 2sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETH-39582</td>
<td>So08-01 A1</td>
<td>57-61 cm</td>
<td>59 cm</td>
<td>400</td>
<td>40</td>
<td>493</td>
<td>307</td>
<td>400</td>
</tr>
<tr>
<td>ETH-39583</td>
<td>So08-01 A3</td>
<td>65-68.5 cm</td>
<td>250.95 cm</td>
<td>2835</td>
<td>40</td>
<td>3207</td>
<td>2918</td>
<td>3062.5</td>
</tr>
<tr>
<td>ETH-39584</td>
<td>So08-01 B1</td>
<td>49 cm</td>
<td>319.80 cm</td>
<td>4230</td>
<td>40</td>
<td>4870</td>
<td>4700</td>
<td>4785</td>
</tr>
<tr>
<td>ETH-39585</td>
<td>So08-01 B1</td>
<td>66-66.5 cm</td>
<td>337.05</td>
<td>825</td>
<td>40</td>
<td>5596</td>
<td>5326</td>
<td>5461</td>
</tr>
</tbody>
</table>

All material dated were plant macrofossils. $^{14}$C ages calibrated using OxCal v4.1.7.

Atmospheric data from Reimer et al. (2009).

*1) from Hajdas et al. (1993)

Tab. 2. Sediment composite Lake Soppensee

<table>
<thead>
<tr>
<th>Section Name</th>
<th>Photo length (cm)</th>
<th>used in composite</th>
<th>Composite Depth Bottom (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>So08-01 A1</td>
<td>83.3</td>
<td>0-83.3 cm</td>
<td>83.3</td>
</tr>
<tr>
<td>So08-01 A2</td>
<td>100.9</td>
<td>0-100.9 cm</td>
<td>184.2</td>
</tr>
<tr>
<td>So08-01 A3</td>
<td>100.1</td>
<td>0-90 cm</td>
<td>274.2</td>
</tr>
<tr>
<td>So08-01 B1</td>
<td>72.9</td>
<td>3.4-72.9 cm</td>
<td>343.7</td>
</tr>
<tr>
<td>So08-01 B2</td>
<td>98.9</td>
<td>0-74.2 cm</td>
<td>417.9</td>
</tr>
<tr>
<td>So08-02 C1</td>
<td>71.7</td>
<td>10.8-71.7 cm</td>
<td>478.8</td>
</tr>
<tr>
<td>So08-02 C2</td>
<td>96.3</td>
<td>0-96.3 cm</td>
<td>575.1</td>
</tr>
<tr>
<td>So08-02 C3</td>
<td>96.2</td>
<td>0-93.5 cm</td>
<td>667.6</td>
</tr>
<tr>
<td>So08-01 C2</td>
<td>93.8</td>
<td>70.5-93.8 cm</td>
<td>691.9</td>
</tr>
<tr>
<td>So08-01 C3</td>
<td>93.2</td>
<td>0-93.2 cm</td>
<td>785.1</td>
</tr>
</tbody>
</table>
Fig. 1. Age-depth depositional model for Lake Soppensee. Boundaries set at 562 cm, 500 cm, 365 cm, 110 cm.
A.1.c. Baldeggsee

**Tab. 1.** $^{14}$C-ages for age model in addition to dates from Monecke et al. (2006).

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Core Section</th>
<th>Section Depth</th>
<th>Mean Composite Depth</th>
<th>$^{14}$C age BP ±</th>
<th>INTCAL 09 up 2sig</th>
<th>INTCAL 09 low 2sig</th>
<th>INTCAL 09 av. 2sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETH-</td>
<td>Ba09-02 B2</td>
<td>68-69.5 cm</td>
<td>570.7 cm</td>
<td>4540 ± 35</td>
<td>5444</td>
<td>5152</td>
<td>5298</td>
</tr>
<tr>
<td>ETH-</td>
<td>Ba09-02 B3</td>
<td>64-64.5 cm</td>
<td>666.5 cm</td>
<td>6615 ± 40</td>
<td>7566</td>
<td>7436</td>
<td>7501</td>
</tr>
<tr>
<td>ETH-</td>
<td>Ba09-02 C2</td>
<td>78-97 cm</td>
<td>826.1 cm</td>
<td>8935 ± 45</td>
<td>10233</td>
<td>10114</td>
<td>10173</td>
</tr>
</tbody>
</table>

All material dated were plant macrofossils. $^{14}$C ages calibrated using OxCal v4.1.7.

Atmospheric data from Reimer et al. (2009).

**Tab. 2.** Sediment composite Lake Baldegg

<table>
<thead>
<tr>
<th>Section Name</th>
<th>Photo length (cm)</th>
<th>used in composite</th>
<th>Composite Depth Bottom (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ba09-04 short</td>
<td>109.6</td>
<td>0-93.8 cm</td>
<td>93.8</td>
</tr>
<tr>
<td>Ba09-01A2</td>
<td>101.4</td>
<td>1-58.2 cm</td>
<td>151.1</td>
</tr>
<tr>
<td>Ba09-05A2</td>
<td>74.3</td>
<td>2.5-63 cm</td>
<td>211.7</td>
</tr>
<tr>
<td>Ba09-01A3</td>
<td>114.3</td>
<td>13.1-122.1 cm</td>
<td>320.8</td>
</tr>
<tr>
<td>Ba09-05B1</td>
<td>81.6</td>
<td>6.9-65.3 cm</td>
<td>379.3</td>
</tr>
<tr>
<td>Ba09-01B1</td>
<td>86.1</td>
<td>21.4-66.1 cm</td>
<td>424.1</td>
</tr>
<tr>
<td>Ba09-01B2</td>
<td>102.1</td>
<td>0-88.8 cm</td>
<td>512.9</td>
</tr>
<tr>
<td>Ba09-02B1</td>
<td>86.3</td>
<td>7.3-86.3 cm</td>
<td>592</td>
</tr>
<tr>
<td>Ba09-02B2</td>
<td>98.9</td>
<td>0-85.4 cm</td>
<td>677.4</td>
</tr>
<tr>
<td>Ba09-01C1</td>
<td>85.3</td>
<td>4.6-52.2 cm</td>
<td>725.1</td>
</tr>
<tr>
<td>Ba09-02B3</td>
<td>100.8</td>
<td>25.4-84.7 cm</td>
<td>784.5</td>
</tr>
<tr>
<td>Ba09-01C2</td>
<td>102.9</td>
<td>20.7-80 cm</td>
<td>843.9</td>
</tr>
<tr>
<td>Ba09-02C1</td>
<td>88.2</td>
<td>5.7-88.2 cm</td>
<td>925.5</td>
</tr>
<tr>
<td>Ba09-02C2</td>
<td>94.4</td>
<td>0-88 cm</td>
<td>1013.5</td>
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<tr>
<td>Ba09-01D1</td>
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<td>19.3-87 cm</td>
<td>1081.2</td>
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<tr>
<td>Ba09-01D2</td>
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<td>0-97 cm</td>
<td>1178.1</td>
</tr>
<tr>
<td>Ba09-01D3</td>
<td>106.2</td>
<td>0-106.2 cm</td>
<td>1284.3</td>
</tr>
</tbody>
</table>
Fig. 1. Age-depth depositional model for background sedimentation (=excluding event layers) in Lake Baldegg. Boundary set at 360 cm.
A.2. XRF data

Here, the detailed XRF raw data is presented. The Avaatech XRF Core Scanner uses a Rh x-ray source and a Canberra X-Pips Si PIN diode detector containing Ag and Be. The analytical system is constantly flushed with Helium to prevent contamination.

The following plots present total XRF counts per area on the y-axis. For analyses on Gerzensee sediments the area per measurement was 12 x 2 mm. For the other archives an area of 12 x 1 mm per measurement was analyzed.

The x-axis presents composite depth in cm. For Gerzensee sediments the Laacher See Tephra was used as a reference level: to enable correlation with previously analyzed cores, the LST was assigned a depth of 272 cm. For the other archives, 0 cm represents the sediment surface.
A.2.a. Gerzensee

- Al_Area
- K_Area
- Ti_Area
- Rb_Area
- Zr_Area
Appendix

A.2.b. Burgäschisee

[Graphs showing time series for different elements (Al, K, Ti, Rb, Zr)]
A.2.c. Soppensee

- Al
- K
- Ti
- Rb
- Zr
A.2.d. Baldeggersee

- \( \text{Al}_{\text{Area}} \)
- \( \text{K}_{\text{Area}} \)
- \( \text{Ti}_{\text{Area}} \)
- \( \text{Rb}_{\text{Area}} \)
- \( \text{Zr}_{\text{Area}} \)
A.3. Sediment core images

A.3.a. Gerzensee Core GEM
A.3.b. Burgäschisee

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>BurgC 0-1m</th>
<th>BurgC 1-2m</th>
<th>BurgC 2-3m</th>
<th>BurgC 3-4m</th>
<th>BurgC 4-5m</th>
<th>BurgC 5-6m</th>
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<tbody>
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<td></td>
<td></td>
<td></td>
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A.3.c. Soppensee Core So08
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