The potential of non-alpine lakes for quantitative palaeotemperature reconstructions based on subfossil chironomids: A comparative palaeolimnological study from southern Norway

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Abstract

In this study, Holocene mean July temperatures were reconstructed quantitatively based on subfossil chironomid remains. The specific goal was to evaluate whether lakes located below the modern tree line are appropriate sites for the chironomid-based reconstruction of small-scale temperature variations. On this account, the main questions were whether the water chemistry and physical conditions of the chosen lakes can be regarded as stable during the Holocene, whether the chironomid assemblages react sensitively to Holocene temperature fluctuations, and whether they record human impact. To answer these questions, the sediments of the lakes Reiarsdalsvatnet (245 m asl, maximum water depth: 9.2 m, boreo-nemoral) and Isbenttjønn (787 m asl, maximum water depth: 9.4 m, northern boreal) were studied in a multi-proxy approach, including age-depth modelling based on radiocarbon dating, chironomid and pollen analyses, and the analyses of carbon, nitrogen, sulphur and biogenic silica.

The reconstructed environmental conditions can be summarised as follows: By 9,900 cal. BP, the region around Reiarsdalsvatnet was covered with a mixed deciduous-coniferous forest, and *Betula-Pinus* woodland was present around Isbenttjønn after 9,300 cal. BP. The onset of the formation of organic sediment in the lakes occurred in the Preboreal and Boreal chronozone, respectively. By 9,600 cal. BP in Reiarsdalsvatnet and by 8,600 cal. BP in Isbenttjønn, soil stability in the catchments was reached. A distinct opening of the landscape together with other signs of human impact is seen from 2,700 cal. BP at Reiarsdalsvatnet. In the Isbenttjønn profile, signs of human activity are evident from 3,300 cal. BP, but a distinct opening of the vegetation occurs not until 1,400 cal. BP. Though human activity is indicated at both lakes during the last millennia, humans seem to have changed the vegetation around the lakes only gradually. Both lakes were generally oligotrophic during most of the Holocene and only in the youngest sediments increasing productivity at low levels is indicated. Well oxygenated conditions prevailed in the hypolimnion of Reiarsdalsvatnet and good to moderate hypolimnetic oxygen conditions in the one of Isbenttjønn. Concluding, both lakes and their catchments have undergone only minor changes during the Holocene and the water chemistry and physical conditions are regarded as stable.

In a further step, Holocene mean July temperatures were reconstructed quantitatively based on the chironomid data using transfer functions. By the application of several evaluation procedures, it was possible to differentiate between phases of reliable and phases of less reliable reconstructions. For this, mean July temperatures were also inferred from the pollen data to enable a comparison with independent temperature reconstructions. The results of this comparison show very similar centennial to millennial-scale trends during most of the studied period in the chironomid- and the pollen inferred temperatures of both lakes. Only in the youngest sediments of Isbenttjønn, human impact could be accounted to be responsible for unreliably high chironomid-inferred temperatures, even though the impact was only moderate. Apart from this period, the chironomid-inferred temperatures of both lakes generally show similar Holocene temperature trends: Temperatures increase until c. 8,000 cal. BP and maximum Holocene temperatures are reached between 7,600 cal. BP and 7,200 cal. BP. Until c. 4,500 cal. BP, stable temperatures at high level are recorded. Thereafter, temperatures decrease slowly until they drop clearly after 1,500 cal. BP. These trends resemble widely known features of the Holocene summer temperature development in Scandinavia, as assessed by the comparison to records of Norwegian Holocene glacier variations, of Holocene changes in net precipitation in southern Sweden, and of inferred air temperatures in central Greenland.

In this study is demonstrated that subfossil chironomids from the studied non-alpine lakes do react sensitive to small-scale summer temperature fluctuations. The results point to the importance of a cautious selection of study sites and to the fact that a thorough knowledge about the catchment-lake system and a thorough evaluation of the reconstructed temperatures is crucial to obtain reliable results. In summary, these suggest that non-alpine lakes are high potential sites for the reconstruction of small-scale temperature variations based on chironomids.

Zusammenfassung

In dieser Arbeit wurden mittlere Julitemperaturen für das Holozän anhand von paläolimnologischen Untersuchungen der Sedimente zweier südnorwegischer Seen rekonstruiert. Die Rekonstruktionen basieren auf der Analyse von subfossilen Zuckmückenlarven (Chironomidenlarven). Ziel dieser Studie war herauszufinden, ob subfossile Chironomiden aus Seen, die unterhalb der heutigen Waldgrenze liegen, für eine quantitative Rekonstruktion von holozänen Temperaturschwankungen geeignet sind. Den Schwerpunkt bildeten die Fragen, ob die wasserchemischen und physikalischen Bedingungen in den untersuchten Seen während des Holozäns als stabil bezeichnet werden können, ob die Chironomiden sensibel auf holozäne Temperaturschwankungen reagieren und ob menschlicher Einfluss im Einzugsgebiet der Seen durch Veränderungen in den Chironomidengesellschaften aufgezeichnet wird. Untersucht wurden dafür die mittels Radiokarbonmethode datierten Sedimente des Reiarsdalsvatnet (245 m ü. NN, maximale Wassertiefe: 9.2 m, Mischwaldzone) und des Isbenttjønn (787 m ü. NN, maximale Wassertiefe: 9.4 m, nördliches Boreal). Die Multiproxy-Analysen der Sedimente umfassten die Bestimmung der subfossilen Chironomiden, Pollenanalysen und Analysen des Kohlen- und Stickstoffs, des Schwefels und des biogenen Siliziums.

Die wichtigsten Ergebnisse der Rekonstruktion der Umweltgeschichten der Seen sind folgende: Durch die Pollenuntersuchungen konnte Waldbedeckung in der Umgebung des Reiarsdalsvatnet ab 9,900 cal. BP und am Isbenttjønn ab 9,300 cal. BP nachgewiesen werden. Die Ablagerung organischer Sedimente in den Seen begann im Präboreal bzw. Boreal. Die Böden im Einzugsgebiet des Reiarsdalsvatnet sind seit 9,600 cal. BP und im Einzugsgebiet des Isbenttjønn seit 8,600 cal. BP stabil. Nach 2,700 cal. BP konnten eine Auflichtung der Vegetation und erste Hinweise auf anthropogenen Einfluss im Einzugsgebiet des Reiarsdalsvatnet festgestellt werden. Im Profil des Isbenttjønn sind Anzeichen menschlicher Aktivität seit 3,300 cal. BP zu finden, jedoch wird eine Auflichtung der Vegetation erst nach 1,400 cal. BP deutlich. Obwohl es in den Sedimenten beider Seen Hinweise auf die lokale Präsenz des Menschen während des letzten Jahrtausends gibt, hat dieser die Vegetation in den Einzugsgebieten nur graduell verändert. Beide Seen sind während des Holozäns überwiegend oligotroph, nur in den jüngsten Sedimenten konnte eine geringe Zunahme der seeinternen Produktivität nachgewiesen werden. Im Hypolimnion des Reiarsdalsvatnet herrschten gute, in dem des Isbenttjønn gute bis mäßige Sauerstoffverhältnisse. Zusammenfassend wird festgestellt, dass beide Seen während des Holozäns nur geringen Veränderungen unterlagen und somit als stabil betrachtet werden können.

In einem zweiten Schritt wurden die mittleren Julitemperaturen auf Grundlage der Chironomidenanalysen und mit Hilfe von Transferfunktionen rekonstruiert. Durch die

Anwendung verschiedener Evaluierungsverfahren war es möglich, Phasen verlässlicher von Phasen weniger verlässlicher Temperaturrekonstruktionen zu unterscheiden. Um einen direkten Vergleich mit unabhängigen Daten zu ermöglichen, wurden zudem mittlere Julitemperaturen auf Grundlage der Pollenanalysen rekonstruiert. Die Ergebnisse dieses Vergleiches zeigen für beide Seen, dass die aus Chironomiden und die aus Pollen abgeleiteten mittleren Julitemperaturen während eines Großteils des untersuchten Zeitraumes sehr ähnlich verlaufen. Der wichtigste Zeitabschnitt, für den die chironomidenbasierten Temperaturrekonstruktionen durch die Evaluationsverfahren als „weniger verlässlich" erkannt wurden, ist der der jüngsten 1,300 Jahre des Isbenttjønn. Dieses wurde höchst wahrscheinlich durch menschlichen Einfluss im Einzugsgebiet ausgelöst, obwohl der Einfluss sehr begrenzt blieb. Beim Vergleich zwischen beiden untersuchten Seen zeigen die chironomidenbasierten Temperaturrekonstruktionen sehr ähnliche Verläufe. Die Temperaturen steigen bis ca. 8,000 cal. BP an und erreichen ihr holozänes Temperaturmaximum zwischen 7,600 cal. BP und 7,200 cal. BP. Stabil hohe Temperaturen sind bis ca. 4,500 cal. BP zu beobachten. Ab 4,500 cal. BP nehmen die Temperaturen zunächst langsam ab und gehen ab ca. 1,500 cal. BP deutlichen zurück. Dieser Verlauf spiegelt die bekannte Temperaturentwicklung in Skandinavien wieder, was durch den Vergleich mit Datensätzen von norwegischen Gletscherschwankungen, mit rekonstruierten Nettoniederschlägen in Südschweden und mit rekonstruierten grönländischen Sommertemperaturen nachgewiesen wurde.

Mit dieser Arbeit konnte gezeigt werden, dass subfossile Chironomiden aus den untersuchten Seen sensibel auf Schwankungen der holozänen Sommertemperaturen reagieren. Die Ergebnisse weisen auf die große Bedeutung einer umsichtigen Wahl der zu untersuchenden Seen hin, und darauf, dass ein umfassendes Wissen über das System von See und Einzugsgebiet und eine Evaluation der Temperaturrekonstruktionen notwendig ist, um verlässliche Ergebnisse zu erhalten. Zusammenfassend konnte gezeigt werden, dass Sedimente aus Seen, welche unter der heutigen Waldgrenze liegen, ein großes Potential für die chironomidenbasierte Rekonstruktionen holozäner Temperaturschwankungen bilden.

Chapter 1: Introduction

‘Swiss Hostel Offers View of Crumbling Peak as Glacier Retreats’ (New York Times, 13 August 2006) – ‘US fires “due to climate change”’ (The Times, 07 July 2006) – ‘Old Ways of Life are Fading as the Arctic Thaws’ (New York Times, 20 October 2005). Headlines like these, dealing with climate change and its impact on today’s societies, can be encountered more and more often in international newspapers. Such articles raise the question whether natural catastrophes will happen more frequently in the future due to anthropogenic perturbations of the climate system. This shows that climate change has become an important issue in the consciousness of the general public and politicians. Vigorous political debates have been and are taking place about the question if the increase in mean temperature measured in the last century is caused by human impact, and if so, what consequences need to be drawn from this knowledge. An outstanding example of such a debate is the discussion about publications of Mann *et al.* (Mann 1999; Mann et al. 1998). Mann *et al.* reconstructed Northern Hemisphere mean temperatures of the last millennium. The graph related to this reconstruction became widely known as the ‘hockey-stick’ and is a prominent part of the 2001 summary report of the Intergovernmental Panel on Climate Change (IPCC 2001). A discussion about the reconstruction’s data basis and the statistical methods arose soon after the publication and involved not only scientists, but also politicians such as members of the U.S. Congress (see Nature 2005, e.g. Schiermeier 2005). A stop on the debate was reached in 2006, when the U.S. National Academy of Sciences published a report largely endorsing the work of Mann *et al.* (Brumfield 2006). This debate throws light on the importance and relevance of climate research for today’s societies.

All predictions about future climate development under human impact are based on climate models. These depend on knowledge about ‘natural’ climate variability, since all anthropogenic perturbations of the climate are superimposed on these variations (Bradley 2000). Until the mid 1990’s, the Holocene (c. 11,500 cal. BP to present, O'Brien *et al.* 1995) was believed to be a climatically very stable period, with high annual mean temperatures and low temperature variability, as is seen in the Greenland ice-core records (Dansgaard *et al.* 1993). Bond *et al.* (1997) proposed in the late 1990’s that Holocene climate was subject to abrupt shifts. These shifts, recognised in marine sediment cores from the North Atlantic, are indicated by ice-rafted debris (IRD) events. Since then, empirical evidence from different archives suggests that significant temperature variability has occurred during much of the Holocene (Oldfield 2003).

Knowledge about the amplitudes and frequencies of these Holocene climate variations is required as a basis for climate models and for the evaluation of their outputs. The ideal data basis would be many centuries or millennia long time-series of quantitative meteorological data from globally widespread localities. Since instrumental records are generally restricted to the last 100 to 150 years, information from palaeoclimate archives is needed to track climate further back in time (Bradley 2000).

One of these archives is the group of lacustrine sediments. Lake sediments are globally widespread records of past environment and climate, as lakes exist in most climate regimes. Their sediments are mostly continuous, span long periods of time and yield palaeoclimate information at moderate to high temporal resolution (Fritz 2003). Thus lake sediments are well suited for climate reconstructions. Still, one specific problem becomes evident, when comparing the goal of Holocene climate reconstructions based on lake sediments to palaeolimnological climate reconstruction of earlier periods. The Holocene is the period in which the transition from pre-human or 'natural' conditions to conditions influenced by human beings took place. Since the impact of humans on the ecosystem began much earlier than industrialisation, the possibility of human activity influencing the natural system has to be taken into account whenever interpreting sediment records in terms of climate change. Two lines of dealing with this problem have become state-of-the-art. Process studies focus on the understanding of how a forcing factor is mirrored in the sediment record (e.g. Filippi et al. 1998; Köster and Pienitz 2006; Ohlendorf and Sturm 2001). If these processes are understood, a direct inference of changes in the forcing factor from the sediment record is possible. In multi-proxy studies, the development of the lake system is tracked by the study of many different proxies (e.g. Ammann 2000; Birks et al. 2000; Birks and Birks 2006; Caseldine et al. 2003; Lotter 2003; Solovieva and Jones 2002; Wohlfarth et al. 2004). The idea is that different forcing factors are reflected in different sediment attributes. Thus when studying different proxies, it should be possible to separate and reconstruct the influence of each of the forcing factors through time.

In palaeolimnological studies, various physical, chemical and biological proxies can be examined. Among these proxies, the ones from which quantitative climate data can be derived are especially valuable for the reconstruction of Holocene climate variability. In this context, quantitative climate reconstructions from biological proxy data involving transfer functions have become an important tool in the last 20 years (e.g. Birks 1995; ter Braak et al. 1993), and the study of subfossil chironomids has received special attention during the last decade (e.g. Brooks and Birks 2001; Heiri et al. 2004; Larocque and Hall 2003; Levesque et al. 1993; Rosén et al. 2003; Walker and Cwynar 2006; Walker et al. 1991b).

Chironomids and palaeolimnology

Chironomids or non-biting midges (Insecta: Diptera: Chironomidae) are the most widely distributed and often the most abundant group of insects in freshwaters

(Armitage 1997). The family is spread worldwide and it is estimated that more than 10,000 species exist (Armitage 1997). Their life cycle covers the egg stage, four larval instars, a pupal stage, and the adult (imago), (*Fig. 1.1*).

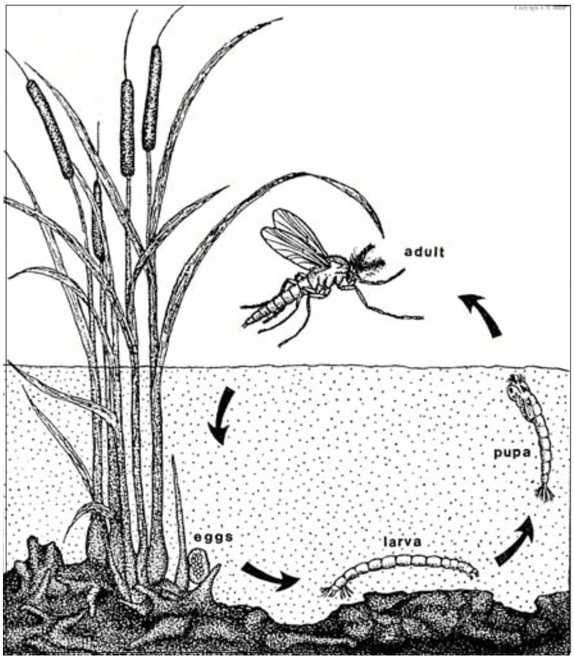


Figure 1.1: Typical life cycle of aquatic Chironomidae, not to scale. Source: *drawn by Dr. Shirley Balla and kindly provided by Mark Lund (2005).*

The majority of the chironomid larvae are aquatic, mostly living in lacustrine environments, but there are also species that live in marine or terrestrial environments (Armitage 1997). They can be classified based on functional feeding groups (Cummins and Merrit 1984), such as collector-gatherers, collector-filterers, scrapers, shredders, predators, and piercers. The analysis of chironomid assemblages has long been recognised as an important tool for the classification of lakes (e.g. Brundin 1949; Sæther 1979; Thienemann 1913/14, 1954; Wiederholm 1980). Chironomids are especially suitable for palaeolimnological studies, since

- chironomid larvae are numerous in most limnic environments,
- chironomid faunas in lakes are highly diverse,
- chironomid species are adapted to particular ecological conditions, and
- head-capsules of chironomid larvae are strongly sclerotised and often well preserved in lake sediments (Hofmann 1988).

In the second half of the 20th century, many palaeolimnological studies used subfossil chironomid remains to study the palaeoecology of lakes to infer past environments (e.g. Brodin 1990; Hofmann 1971; Johnson et al. 1990; Kansanen 1985; Wiederholm and Eriksson 1979). Chironomids are not adapted to any single variable, but to the full range of environmental conditions extant within the normal range of their presence (Walker and Mathewes 1987b). Thus, very different aspects of lake evolution have been studied such as trophic state (Brodersen et al. 2001; Brodin 1982; Little et al. 2000; Sæther 1979; Wiederholm and Eriksson 1979), human impact (Heiri and Lotter 2003; Little and Smol 2000), pollution history (Kansanen 1985), acidification (Brodin 1990; Brodin and Gransberg 1993) and salinity (Heinrichs et al. 1999; Walker et al. 1995). These studies give qualitative results as they are generally based on the idea of indicator species being characteristic of different environmental aspects of lakes.

During the last decades of the 20th century, palaeoecologists began to develop a new approach towards palaeoenvironmental reconstructions. Correlations of subfossil chironomid assemblages from sediment surfaces of lakes and instrumental environmental data were studied using multivariate methods. The evolving calibration data-sets are used to establish a tool for quantitative environmental reconstruction, i.e., transfer functions. With this approach, the correlation of subfossil chironomid assemblages and environmental variables such as nutrient status (Brooks et al. 2001; Lotter et al. 1998), palaeosalinity (Heinrichs et al. 2004; Walker et al. 1995) and hypolimnic oxygen (Quinlan and Smol 2002) were quantified and used for palaeoecological reconstructions. However, as pointed out below, the most important variable to influence chironomid assemblages has been shown to be temperature. Battarbee (2000) suggests that the most promising approach to direct palaeotemperature reconstructions is the one based on chironomids.

Chironomid-inferred palaeotemperatures

In the 1980's a vigorous scientific discussion arose about the question whether temperature or other environmental variables were most important for the composition of chironomid assemblages in lakes. Walker and Mathewes (1987a; 1987b; 1989) stated that temperature plays the major role in explaining the distribution and abundance of chironomid taxa. In contrast, Hann and Warner (Hann et al. 1992; Warner and Hann 1987) argued that local factors such as trophic state, substrate, pH, and others are more influential to chironomid abundance and distribution than climate. In this discussion, Walker *et al.* (1991b) analysed surface sediment samples of 33 lakes at the Canadian East coast together with environmental data by means of multivariate statistics. They were able to show that distributions of chironomids were significantly correlated with surface-water temperature. Later, Walker *et al.* (1992) in their reply to Hann *et al.* (1992) stress the importance of scale in the explanation of chironomid distribution by temperature. Since they were interested in large-scale shifts in climate at the Glacial – Interglacial transition, they suggested that the focus should not be on small-scale processes, but on broad-scaled variations (Walker *et al.* 1992).

Since then, modern chironomid – temperature calibration data-sets have been established for Canada (Barley et al. 2006; Walker et al. 1997; Walker et al. 1991b), the Alps (Lotter *et al.* 1997), northern Finland (Olander et al. 1999; Olander et al. 1997), northern Sweden (Larocque *et al.* 2001), Norway (Brooks and Birks 2001,, unpublished) and New Zealand (Woodward and Shulmeister in press). Based on these calibration data-sets, various studies have demonstrated the strength of chironomid-inferred summer temperature reconstructions for the Late Glacial to Early Holocene transition (e.g. Brooks and Birks 2000, 2001; Cwynar and Spear 2001; Heiri and Millet 2005; Levesque et al. 1997; Porinchu et al. 2003; Walker et al. 1991a). For the reconstruction of smaller-scale temperature variations during the Holocene, studies of chironomid-inferred summer temperatures also give promising results (e.g. Bigler et al. 2002; Caseldine et al. 2003; Heiri et al. 2003; Langdon et al. 2004; Larocque and Hall 2004; Rosén et al. 2001; Rosenberg et al. 2004; Velle et al. 2005a). Laroque and Hall (2003) demonstrated that chironomid-inferred summer temperatures mirror changes in historical meteorological data well. By comparing meteorological data and chironomid-inferred palaeotemperatures for the last century, they conclude that chironomids are sensitive enough to record small-scale temperature fluctuations of the magnitude that occurred during the Holocene.

Still, profiles of chironomid-inferred temperatures cannot always be interpreted in a straightforward way. Difficulties arise when periods of increased lake disturbance occur. Heiri and Lotter (2003) showed that in Sägistalsee (Switzerland) chironomid-inferred temperature reconstructions were strongly influenced by increased human impact. When comparing several chironomid-inferred temperature profiles from one region, periods of deviations among sites often cannot be explained climatologically and are attributed to site-specific effects, e.g. changes in lake water pH, trophic state, or hypolimnic oxygen (e.g. Heinrichs et al. 2006; Larocque and Hall 2004; Rosenberg et al. 2004). This difficulty is also apparent in the study of Velle *et al.* (2005a), who compared chironomid-inferred temperatures from six lakes in Norway. The temperature reconstructions show large differences between sites, which Velle ascribes to different local factors, like productivity and water chemistry changes, and to limitations of taxonomic resolution.

Like most other studies reconstructing Holocene temperatures based on chironomids, Velle *et al.* (2005a) chose sites situated close to or above the alpine (in other cases arctic) tree-line (e.g. Bigler et al. 2002; Fallu et al. 2005; Heiri and Lotter 2003; Heiri et al. 2003; Larocque and Hall 2004; Rosenberg et al. 2004; Velle et al. 2005b). This ecotone is regarded as being especially sensitive to climate changes, since lakes on the opposite sides of the tree-line exhibit striking differences in water chemistry and physical conditions (Lotter *et al.* 1999). With regard to the Holocene, it is questionable if these lakes are appropriate sites for chironomid-based summer temperature reconstructions. Here, changes in chironomid assemblages caused by small-scale temperature variations in the Holocene might be overridden by local effects, while this might not be the case when reconstructing the large-scale variations that occurred at the last Glacial – Interglacial transition. Thus sites with a maximum stability in the lake and the catchment during the period of interest might be more suitable to reconstruct small-scale temperature variations.

In this context, two studies from the Swiss Alps add some interesting insights. Heegaard *et al.* (2006) follow up the question if consistent aquatic ecotones exist along an altitudinal gradient in the Swiss Alps. They studied aquatic species-turnover variations in relation to increasing altitude, with special regard to the ecotone of the modern tree-line. The results show that the areas of major species-turnover do not fall together with the modern tree-line. Regarding chironomids, the tree-line has only an indirect influence on species turnover and the main 'ecotones' for chironomids are located in two areas: a belt enveloping 300 m below modern tree-line and one at lower elevations (600 m asl and below 460 m asl, respectively, depending on the statistical distance measure). This suggests that chironomids from lakes located in these altitudes might react more sensitively to temperature changes than the ones from sites located at or above the modern tree-line. Although the results cannot be directly transferred to the situation in other regions, they suggest that lakes below modern tree-line should be considered when working on chironomid-based temperature reconstructions.

In another study from the Swiss Alps, Livingstone *et al.* (2005) analysed the altitude-dependence of the relation between lake surface-water temperature and air temperature in 29 lakes in the Alps. They found two different thermal regimes, with a threshold at the altitude of c. 2000 m asl. This altitude corresponds to the modern tree-line which is located at 1900 – 2000 m asl in this part of the Alps (Lotter *et al.* 1997). Three hypotheses are given as plausible explanations for the difference in thermal regimes (Livingstone *et al.* 2005): 1. The stratification of lakes below the threshold is more stable than in high altitude lakes. The low-altitude lakes would than react to climate forcing only within a thin, mixed surface layer, while high-altitude lakes respond throughout the whole water column. 2. Lakes at lower altitudes are not affected by melt-water from long-lasting snow in the catchment. 3. Differences in the amount and opacity of cloud cover cause the differences in thermal regimes. They conclude that palaeolimnological studies of high-altitude lakes cannot assume that the lakes have always belonged to the same thermal regime. Of special interest in the context of the present chironomid study is the statement that 'summer air temperature might not be the major factor controlling biota in high-altitude lake ecosystems at all' (Livingstone *et al.* 2005).

Concept, background, and goals of the study

This study is part of the international research on Global Change. It focuses on subfossil chironomids and is based on material and unpublished results from the project 'Holocene climatic history and ecological impacts in Setesdal, southern Norway: a quantitative pollen-analytical study' (1996 - 1999) of H.J.B. Birks and S. M. Peglar (Botanical Institute, University of Bergen, Norway; now the Department of Biology). In this project, 11 lakes along a north-south transect in the Setesdal valley were cored, radiocarbon-dated and pollen-analysed. I am indebted to H.J.B. Birks and S. M. Peglar for providing the sediment cores from two of these lakes for my additional chironomid and geochemical analyses, along with the site description of the modern vegetation, the raw AMS^{14}C dates, results of pollen analysis carried out by S. M. Peglar, and the pollen and chironomid modern calibration data-sets for Norway for my statistical analysis and interpretation in this study. Based on these data, the goal of this study is to evaluate the appropriateness of lakes located below modern tree-line for the quantitative chironomid-inferred temperature reconstructions of small-scale summer temperature variations. The study focuses on the following questions:

- Can the water chemistry and physical conditions of non-alpine lakes be regarded as stable during the Holocene?
- Do chironomid assemblages in lakes situated in the zone below modern tree-line and in the deciduous/boreal forest ecotone react sensitively to Holocene temperature fluctuations?
- Do subfossil chironomids from these lakes record human impact?

Multi-proxy analyses of two lake sediment records will be carried out in order to answer these questions. The first lake is located in the boreo-nemoral vegetation zone in an ecologically comparable situation to the sites forming the lower chironomid 'ecotone' suggested by Heegaard *et al.* (2006). The second lake is situated in the northern boreal vegetation zone, corresponding to the second chironomid 'ecotone' located below the modern tree-line in the study of Heegaard *et al.* (2006).

Derived from the questions, the following hypotheses will be tested in this study:

1. Water chemistry and physical conditions of the studied lakes were only subject to minor changes during the Holocene, and can thus be regarded as stable.
2. The small-scale fluctuations of Holocene summer temperatures are recorded in the subfossil chironomid records of the studied lakes.
3. The subfossil chironomid records of the studied lakes are not influenced by human impact.

In a first step, an overview of the study region is given in **Chapter 2** of this study. It comprises geographic, geologic, climatic, vegetational, and archaeological characteristics of the sites. In **Chapter 3** the laboratory and statistical methods used in this study are described. Age-depth models for both sediment records, geochemical data and pollen records are presented in **Chapter 4**. On the basis of these results lake genesis, sedimentation history, and local vegetation development are discussed. In **Chapter 5**, the results of the chironomid analyses are presented and interpreted qualitatively with regard to ecological changes in the lakes during the last c. 10,000 years. In **Chapter 6**, mean July temperatures are reconstructed quantitatively based on the results of the chironomid analyses. These reconstructions are evaluated by means of numerical criteria and by comparisons with the independent pollen-based temperature reconstructions from the same lakes. Subsequently, they are discussed in the context of the palaeoecological reconstructions from Chapters 4 and 5, and of previously published Holocene climate reconstructions. A concluding discussion about the results of this study with respect to the initial hypotheses is presented in **Chapter 7.**

Chapter 2: Regional overview and study sites

Geographical and geological overview

In this study, ‘southern Norway’ is defined as the region south of 61°N. It comprises the area south of the line Sognefjord (north-west) to Lillehammer (north-east) and is limited to the east by the Oslo Graben structure. The two lakes studied are called Reiarsdalsvatnet and Isbenttjønn, located in the Setesdal valley. Setesdal runs over 200 km in a north-south direction from the southern margin of the Hardangervidda plateau at over 1000 m altitude to the south coast at Kristiansand (*Fig. 2.1*). The geology of southern Norway is characterised by the Precambrian Baltic Shield in the south-east and the Norwegian Caledonidian zone in the north and north-west. Both lakes are located on the old landmass of the central southern Precambrian area (*Fig. 2.2*) with granite and gneiss as underlying bedrock (Oftedal 1980, Sigmond 1975).

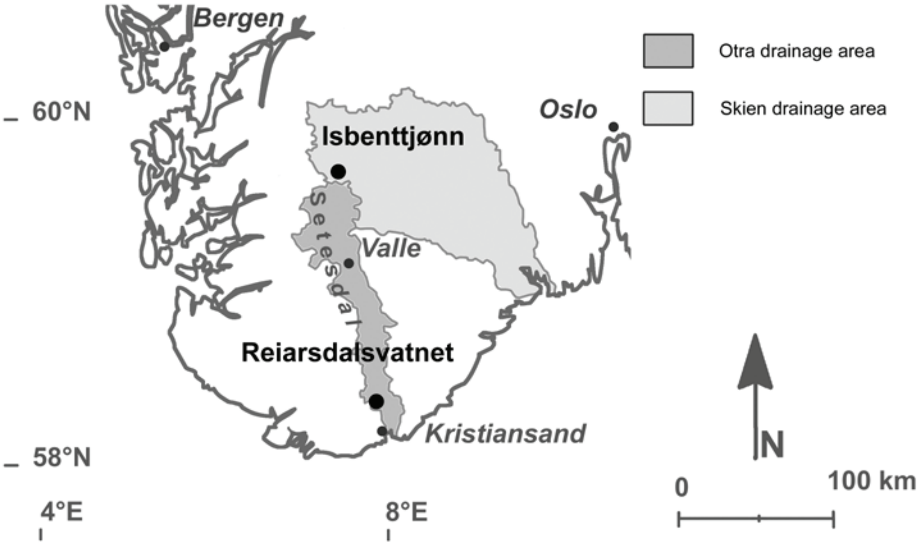


Figure 2.1: Overview of southern Norway showing the study sites Reiarsdalsvatnet and Isbenttjønn and the main river drainage areas. Source: *modified from Norges Geologiske Undersøkelse (2006).*

Climate

The climatological setting of southern Norway is characterised by its location in the zone of westerly winds and by the proximity of the North Atlantic Current. Different gradients influence the climate of southern Norway (Moen 1999) (*Fig. 2.3*): the west-east gradient in precipitation with precipitation maxima in the west (mean annual precipitation at Bergen Florida: 2250 mm, at Oslo Blindern: 763 mm; Norsk Meteorologisk Institutt 2006), the temperature gradient, characterised by decreasing mean temperatures with increasing altitude and latitude (mean annual temperature at

Kristiansand, 22 m asl: 7 °C; at Finse, 1224 m asl: -2.1 °C; Norsk Meteorologisk Institutt 2006), and the west-east gradient in continentality. Setesdal with its north-south orientation is only marginally affected by the precipitation and oceanicity gradients (annual precipitation at Kristiansand: 1380 mm, at Vågsli 1067 mm; Norsk Meteorologisk Institutt 2006). Most influential is the temperature gradient with decreasing temperatures from south to north due to increasing altitude.

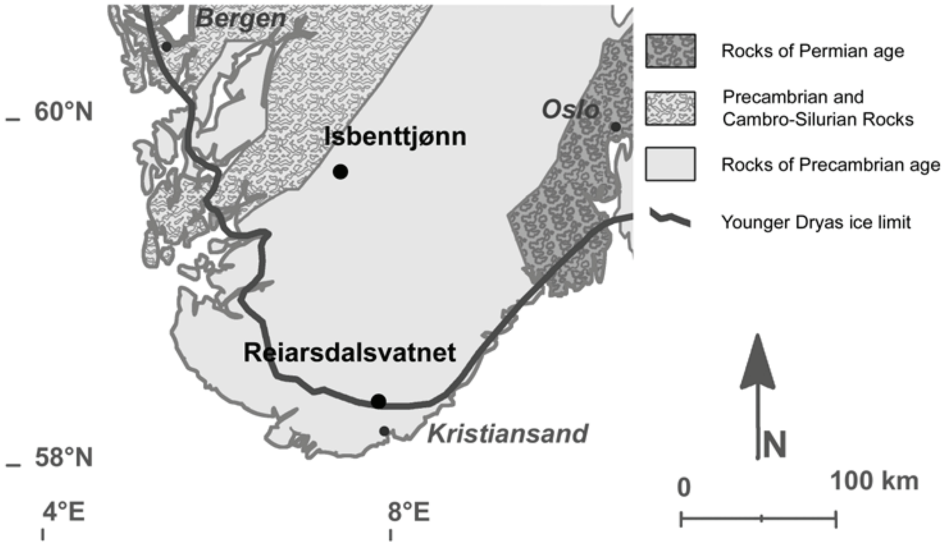


Figure 2.2: Schematic geological map of southern Norway with the study sites Reiarsdalsvatnet and Isbenttjønn marked. The maximum extent of the Younger Dryas ice sheet is indicated by the solid line. Source: *modified from Norges Geologiske Undersøkelse (2006), Andersen (1980), Birks (1994), and Moen (1999).*

Vegetation

Topographical setting and climatological gradients are the most important factors for today's vegetation zones in southern Norway. The typical order of those zones is described in Moen (1999) (*Fig. 2.4*): The southernmost coast of Norway lies within the nemoral zone with its temperate, broad-leaved deciduous woodlands. The transition from nemoral to boreal is formed by the boreo-nemoral vegetation zone. It is characterised by a mixture of coniferous and broad-leaved deciduous woodlands. With increasing altitude, this vegetation type is replaced by the coniferous forests of the boreal zone. This zone is divided into the southern boreal zone, characterised by the presence of alder woodland and patches of deciduous woodland within the coniferous forest, the middle boreal zone, representing most typical coniferous woodlands with mires covering large areas, and the birch woodland of the northern boreal zone including patches of coniferous woodland and large minerotrophic mires. The latter one forms the climatic tree-limit. Above, the low-alpine vegetation is characterised by bilberry heath, juniper - dwarf birch scrub, and willow communities.

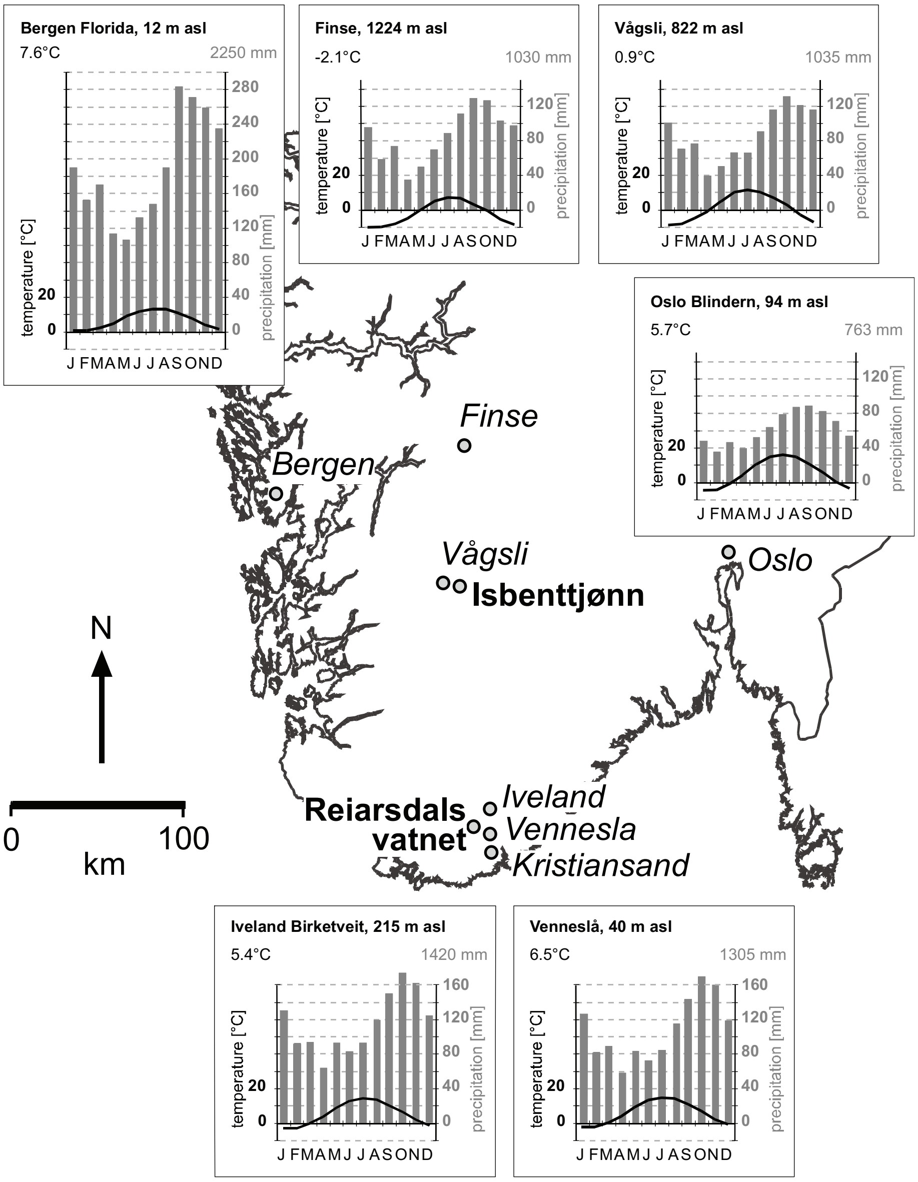


Figure 2.3: Map of southern Norway with climate diagrams from Bergen Florida, Finse, Vågslid, Oslo Blindern, Iveland-Birketveit and Venneslå. The locations of the study sites Reiarsdalsvatnet and Isbenttjønn are indicated. Source: *data from Norsk Meteorologisk Institutt (2006).*

Setesdal cuts through these vegetation zones with the upper limit of the nemoral zone being located at c. 150 m asl, the limit of the boreo-nemoral zone at c. 300 m asl, of the southern boreal zone at c. 500 m asl, of the middle boreal zone at c. 800 m asl, and of the northern boreal zone at c. 1,000 m asl (Moen 1999). Today's pine tree-limit in Setesdal is situated at c. 900 m asl and the tree-line at c. 1,000 m asl is formed by birch (*Betula pubescens* s.l.), (Eide *et al.* 2006).

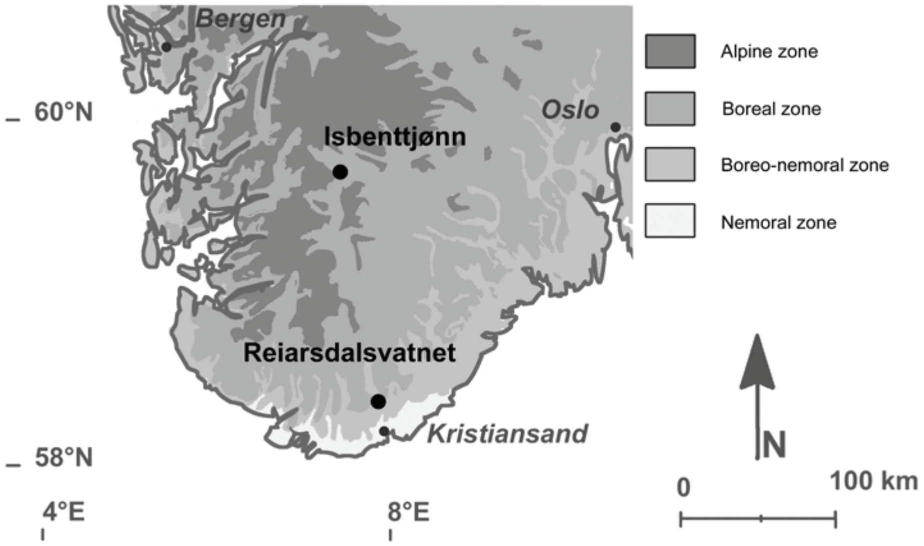


Figure 2.4: Vegetation zones of southern Norway, the study sites Reiarsdalsvatnet and Isbenttjønn are marked. Source: *modified from Moen (1999).*

Deglaciation history and Holocene climatic oscillations

Scandinavia has been intensively affected by the Quaternary glacial – interglacial cycles. The Scandinavian ice shield reached its last glacial maximum between 28 and 22 ka BP. At that time, the ice sheet extended beyond the present Norwegian coast (Sejrup *et al.* 2000). It receeded during the early phase of deglaciation, but extended again during the Younger Dryas. The Younger Dryas is marked by terminal moraines, which are called Ra-moraines in southern Norway (Andersen 1980) (*Fig. 2.2*). The maximum of the Younger Dryas inland ice sheet in south-western Norway lasted c. 100 to 200 years and the final ice retreat started at 11,500 cal. BP (Bondevik and Mangerud 2002). After the Younger Dryas/Holocene transition the ice shield melted rapidly.

In Setesdal, the ice front was located at the Ra-moraines, at least from the Younger Dryas to Preboreal/Boreal time (Anundsen 1985). Setesdal and the Hardangervidda plateau to the north were deglaciated by 10,000 cal. BP (9,000 +/- 200 ^{14}C BP, Andersen 1980, Blystad and Selsing 1988, Moe *et al.* 1978). In their study of pollen and macrofossils from four Setesdal lakes, Eide *et al.* (2006) demonstrate that birch arrived in the upper Setesdal as early as 10,800 cal. BP and pine at 10,000 cal. BP to 9,600 cal. BP. The valley must thus have been ice-free by these times. From fluctuations of remaining plateau glaciers, several major climate oscillations were detected during the Holocene. Nesje (2002) summarises the results of numerous studies and defines the following major events of glacial advances: the 'Erdalen event' at 10,200 cal. BP (9,100 ± 200 ^{14}C BP), the 'Finse event' around 8,500 cal. BP (7,600 ^{14}C BP), one unnamed event at c. 4,200 cal. BP (3,800 ^{14}C BP), and the 'Little Ice Age' which lasted from 300 to 20 cal. BP (AD 1650 to AD 1930). The 'Finse event' can be correlated to the ‘8.2 event’ known from the GRIP and GISP2 ice cores (cf. Dahl and Nesje 1994, 1996, Nesje and Kvamme 1991). With the closest remaining glaciers being located more than 50 km from the upper part of Setesdal (Folgefonna to the east and Hardangerjøkulen to the north-east), Setesdal was not affected by glaciers during the Holocene.

Archaeological evidence for prehistoric human activity

In the following section, all ages are given as calibrated radiocarbon ages, calibrated with the IntCal04 calibration (Reimer *et al.* 2004) and the program CALIB 5.0.1 (Stuiver and Reimer 1993, Stuiver and Reimer 2005). Original ages from the cited papers are shown in brackets.

The pioneer colonisation of the coastal area in southern and western Norway began c. 11,500 cal. BP (9,500 BC), (Bjerk 2004). The colonisation of the whole coast of what is Norway today took place in a few centuries (Bjerk 2004). Anundsen (1996) discusses the physical conditions for the earliest settlement after the deglaciation in Norway. He states that the first opportunity for humans to occupy southern Norway was in the south-west corner of Norway, and the nearest way would have been by boat from a peninsula in the North Sea shelf. Since 10,700 cal. BP (9,500 ^{14}C BP), the shortest way was to cross the sea from Skagen (Denmark) to Norway. Only after 10,700 to 10,100 cal. BP (9,500 ^{14}C BP to 9,000 ^{14}C BP) migration over land, namely from southern Sweden, was possible (Anundsen 1996). During the Mesolithic (*Tab. 2.1*), people lived in small groups close to the sea. They were hunters and gatherers, mainly living on marine resources (Nygaard 1995). However, archaeological evidence is also found from Mesolithic settlements in the southern Norwegian highlands, where people lived by reindeer hunting (Indrelid 1994, Moe *et al.* 1978). In the mountainous area west of Setesdal, Mesolithic settlements have been dated to the period between 7,900 cal. BP and 6,500 cal. BP (7,020 ± 170 ^{14}C BP to 5,670 ± 90 ^{14}C BP), (Bang-Andersen 1986). Mesolithic mountain settlements were located close to lakes or rivers. Trout bones found in settlements dating between c. 7000 cal. BP and 6000 cal. BP (5,000 BC to 4,000 BC) indicate that fish were present in the mountain lakes at that time (Indrelid 2004). The question, whether migration from the coast to the mountains took place seasonally between coastal areas and mountainous areas or if the groups migrated more irregularly over longer distances is not finally resolved (Nygaard 1995). In the forested area between the coast and the highlands, especially in the valleys connecting both, numerous transitory sites should have been present, but only few have been found. These are generally smaller than the high-mountain sites (Indrelid 2004). Bang-Andersen (1996) states that the small number is most likely due to the lack of systematic research in this area.

Table 2.1: Archaeological timetable for southern Norway, compiled from Indrelid (1994), Jokipii (1987), and Larsen (1981).

		Period	**from [BC / AD]**	**to [BC / AD]**	**from [cal. BP]**	**to [cal. BP]**
Modern Age			1550 AD	today	400	today
Middle Ages			1050 AD	1550 AD	900	400
Iron Age	Late Iron Age	Viking	800 AD	1050 AD	1,150	900
		Merovingian	600 AD	800 AD	1,350	1,150
	Early Iron Age	Migration	400 AD	600 AD	1,550	1,350
		Roman	50 AD	400 AD	1,900	1,550
		Pre-Roman	500 BC	50 AD	2,450	1,900
Bronze Age			1800 BC	500 BC	3,750	2,450
Stone Age		Neolithic	3000 BC	1800 BC	4,950	3,750
		Mesolithic	8000 BC	3000 BC	9,950	4,950

The first signs of grain in Norway are found in the 4th millennium BC (Østmo 2004), but people most likely did not live on agro-pastoral production before c. 4,200 cal. BP (3,800 ^{14}C BP), (Ballin 1999, Prescott 1996). Mikkelsen (1989) assumes that the area around Haukelifjell (close to the northern tip of Setesdal) was used for hunting during the Late Neolithic and Bronze Age (*Tab. 2.1*) and that people migrated from the west. Only a few hundred bronze artefacts from the Bronze Age have been found in Norway (Johansen 2004), and none of them have been found in the area of Setesdal (Larsen 1981). The artefacts are unequally spread in time and space over the Bronze Age period, with three core areas: Jæren and Lista in the south-west, around the Oslofjord, and in the area of Trondheimsfjord in the west. Besides various cultural innovations, the introduction of a new house type, which outlasted most of the prehistoric time in Norway, was specific to the Bronze Age. The 'langhus' was up to 25 m long and offered space for people and animals since c. 3000 cal. BP (1000 BC), (Myhre 2004). The latter indicates that animals had to be kept inside during winter and thus winter fodder must have been collected during summer time.

The onset of iron production in Norway took place during the centuries after c. 2,500 cal. BP (500 BC). For domestic iron production, people used bog ore and charcoal, which they produced locally in charcoal kilns (Johansen 1973). Since vast amounts of wood and bog ore were needed to produce iron, the main areas of iron production were not located close to settlements. People favoured the area around the tree-line because of the closeness to fuel (wood) and ore from bogs. In addition, the ecological variability of this area could be used for hunting, pasture, collection of winter food for animals and fishing (Bloch-Nakkerud 1987). In the upper part of Setesdal and in the area around Møsvatn (Vinje, Telemark) numerous charcoal kilns and places for iron production have been discovered and dated to between 1,400 cal. BP and 580 cal. BP (Bloch-Nakkerud 1987, Martens 1988). At the end of the Roman Period (*Tab. 2.1*), farmers have been permanently settled in Setesdal (Larsen 1981). The town of Valle in the upper Setesdal has been an important trading place for iron and skins during the Viking Period (Larsen 1981).

Study sites

Both lakes are located at approximately the same longitude, but at different latitudes and elevations. Reiarsdalsvatnet is situated at 245 m asl in the Venneslå municipality in the county of Vest-Agder (58°19’40” N, 7°47’3” E; *Fig. 2.1*). At the northern end of Setesdal, Isbenttjønn is situated at 787 m asl in the Vinje municipality (county of Telemark), (59°45’55” N, 7°26’9” E; *Fig. 2.1*).

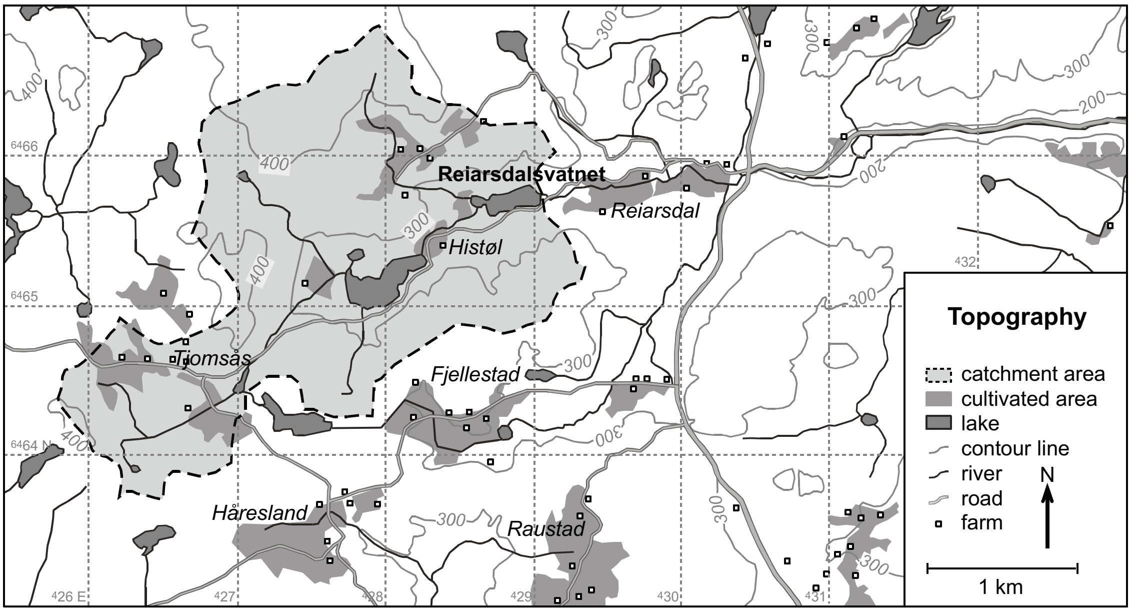


Figure 2.5: Map of the topography around Reiarsdalsvatnet. The catchment of Reiasdalsvatnet is indicated by the dashed line. Source: modified from Statens kartverk (1993).

Reiarsdalsvatnet

Reiarsdalsvatnet is located within the watershed of the River Otra draining to the south through the Setesdal valley (*Fig. 2.1*). It is a small lake with an area of c. 5 ha and a maximum water depth of 9.2 m (*Fig. 2.5, 2.6; Tab. 2.2*). Two small brooks enter Reiarsdalsvatnet in the western part. One of them is the outflow of an unnamed lake situated 500 m south-west of Reiarsdalsvatnet (*Fig. 2.5*). In the eastern part, water leaves Reiarsdalsvatnet through a small outflow. Reiarsdalsvatnet, the unnamed lake and the brook connecting Reiarsdalsvatnet with the River Otra are located in a channel structure running in west-east direction (*Fig. 2.5*). The total catchment of Reiarsdalsvatnet comprises c. 5 km^2 and the area draining directly into Reiarsdalsvatnet is less than 2 km^2 (*Fig. 2.5*). The Precambrian bedrock in the catchment is dominated by granite and gneiss (*Fig. 2.7*), (Norges Geologiske Undersøkelse 2006), with the major part of the catchment being covered by till (*Fig. 2.8*) of the Younger Dryas terminal moraine (Ra-moraine), (*Fig*. 2.2). To the east of the lake, glacio-fluvial sediments are deposited. No carbonates are evident in the catchment, resulting in a pH of 5.5 in the surface water of Reiarsdalsvatnet as measured during fieldwork.

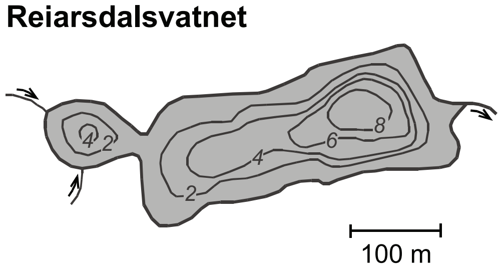


Figure 2.6: Bathymetric map of Reiarsdalsvatnet. Source: *modified from Heiri (2004).*

Climate data of the nearest meteorological stations (Iveland-Birketveit and Venneslå) show that maximum temperatures are reached in July, while a maximum in precipitation is observed in October (c. 170 mm) and the driest month is April (c. 60 mm), (*Fig. 2.3*). The modelled mean July temperature for Reiarsdalsvatnet is 14.3 °C (cf., Chapter 3; A. Odland, unpublished data).

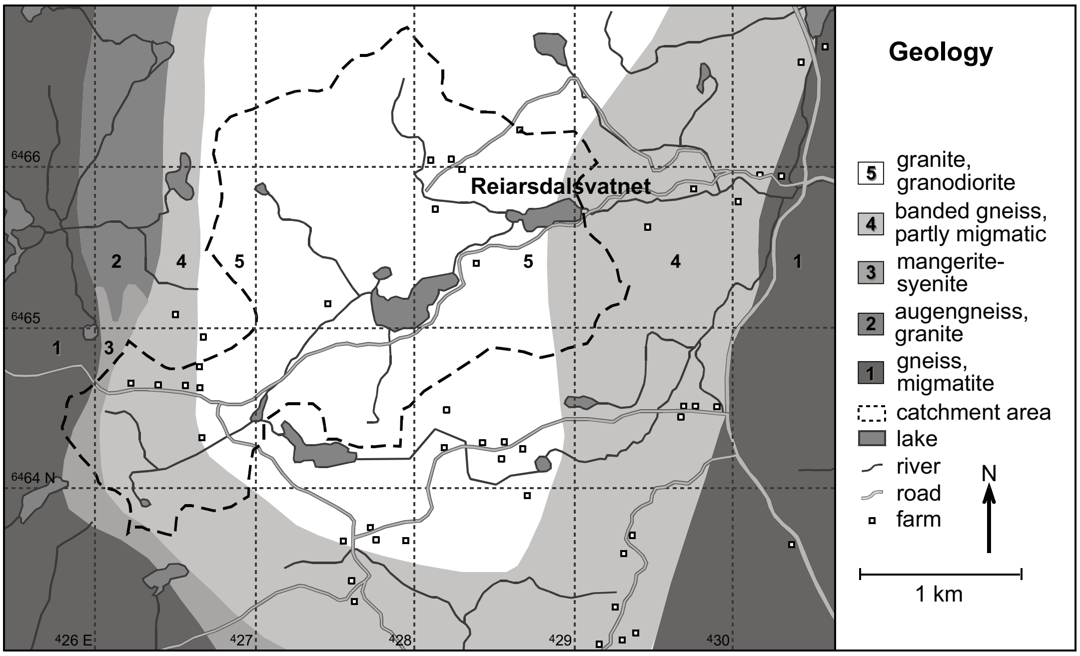


Figure 2.7: Geological map of the area around Reiarsdalsvatnet. Source: *modified from Norges Geologiske Undersøkelse (2006).*

Regarding the vegetation, Reiarsdalsvatnet is situated at the transition between the boreo-nemoral and the southern boreal vegetation zones. Most of the catchment area is covered by mixed coniferous-deciduous forest with *Pinus sylvestris*, *Betula pubescens*, *B. pendula*, *Corylus avellana*, *Quercus robur*, *Alnus glutinosa*, *Sorbus aucuparia*, *Salix caprea*, *S. aurita*, *S. cinerea*, *S. repens*, *Juniperus communis*, *Picea abies*, *Tilia cordata*, and *Populus tremula* being common. The south-facing rocky slope is entirely covered with deciduous forest (*Quercus robur*, *Betula pubescens*, *B. pendula*, *Sorbus aucuparia*, *Corylus avellana*, *Tilia cordata, Populus tremula, Ulmus glabra)*. The lake is fringed by *Carex rostata*, *Myrica gale*, *Molinia caerulea*, and *Vaccinium oxycoccus*. A swamp belt is developed on the western side of Reiarsdalsvatnet and aquatic macrophytes like *Nym-*

Table 2.2: Selected physical, geographical, and environmental characteristics of Reiarsdalsvatnet and Isbenttjønn.

	Reiarsdalsvatnet	**Isbenttjønn**
Altitude [m asl]	245	787
Surface area [ha]	5	5
Max. water depth [m]	9.2	9.4
pH of surface water	5.5	6.4
Mean July temperature [°C]	14.3	10.5
Mean annual precipitation [mm]	1300	1050
Vegetation zone	boreo-nemoral	northern boreal
Water depth of coring site [cm]	834	935
Length of sediment profile [cm]	385	260
Length of organic sediment [cm]	336	215

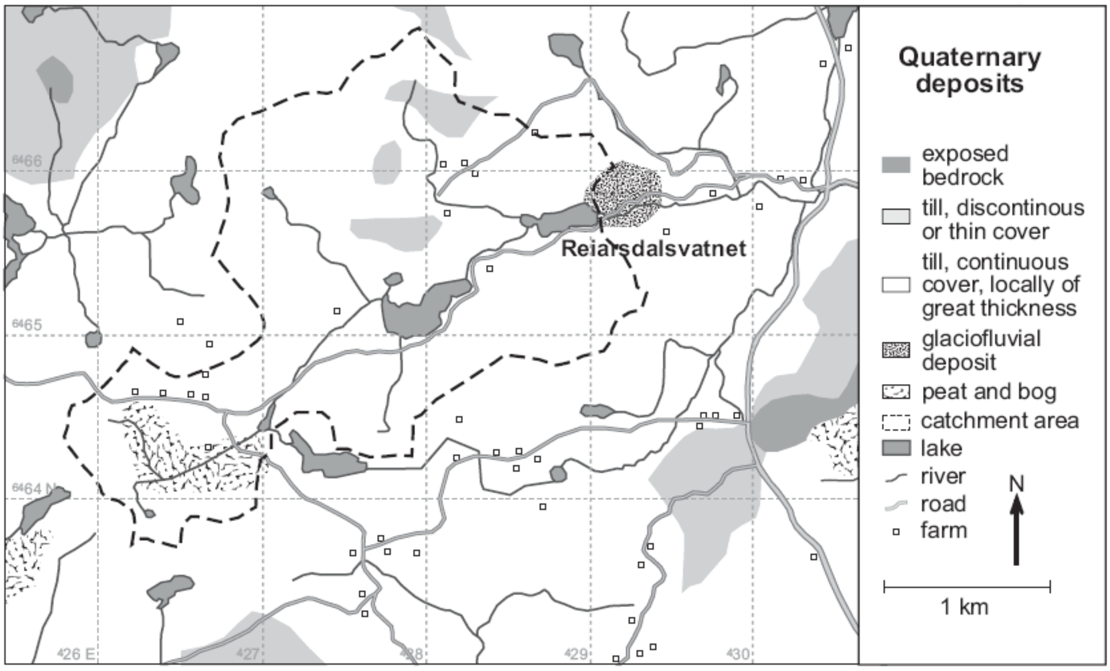


Figure 2.8: The Quaternary sediments in the area of Reiarsdalsvatnet. Source: *modified from Norges Geologiske Undersøkelse (2006).*

phaea alba, *Potamogeton natans*, *Nuphar lutea*, and *Lobelia dortmanna* grow in the lake. The small farms within the catchment (*Fig. 2.5*) do not have any obvious influence on the lake today.

Reiarsdalsvatnet has been the object of former palaeolimnological studies. Heiri *et al.* (2004, 2003a) worked on the within-lake variability of subfossil chironomid assemblages. While in these papers the lake is called Histøl after the name of the small farm located to the south-west of the lake, in the present study the official name given in the topographic maps is used.

Isbenttjønn

Isbenttjønn is located within the drainage area of the River Skien, draining to the south-east (*Fig. 2.1*). Its maximum water depth is 9.4 m, the lake surface area covers c. 5 ha and the surface drainage area c. 1 km² (*Fig. 2.9*). Except from one small brook entering the lake in the western part, only minor inflows into Isbenttjønn are present. To the east, water leaves the lake through a small outflow in the direction of the River Ralfdøla. The Precambrian bedrock in the catchment is dominated by gneiss (Sigmond 1975) (*Fig. 2.10*), locally covered with till (*Fig. 2.11*). There are no signs of carbonate influence, which is supported by the pH of 6.4 in the surface water of Isbenttjønn, measured during fieldwork.

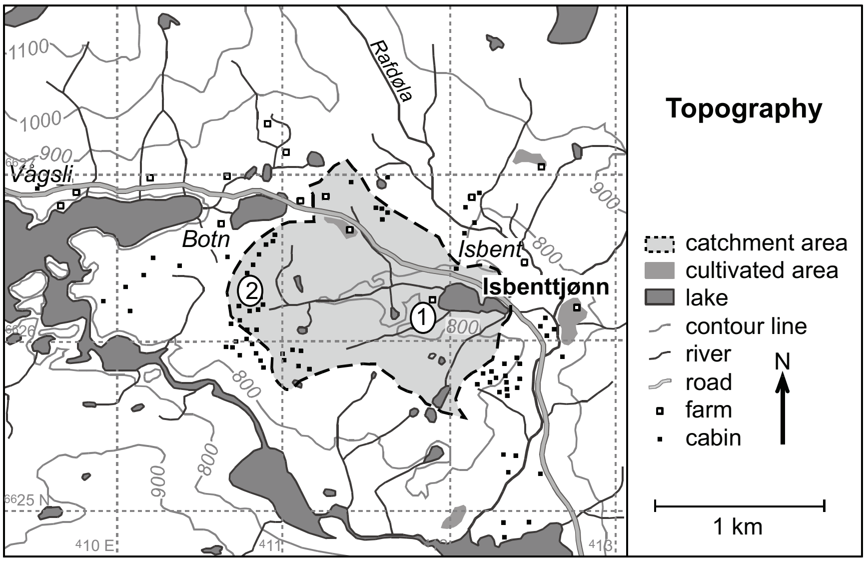


Figure 2.9: Map of the topography around Isbenttjønn. The catchment of Isbenttjønn is indicated by the dashed line. Two areas of settlement are indicated by the numbers 1 and 2. Source: *modified from Statens kartverk (1994).*

The meteorological station of Vågsli is situated close to Isbenttjønn (*Fig. 2.9*). Maximum precipitation sums occur in October (130 mm) and minimum sums in April (40 mm), while the maximum temperature is reached in July (11°C) and minimum temperature in January (-9°C), (*Fig. 2.3*). For Isbenttjønn itself, the modelled mean July temperature is 10.5°C (cf., Chapter 3; A. Odland, unpublished data).

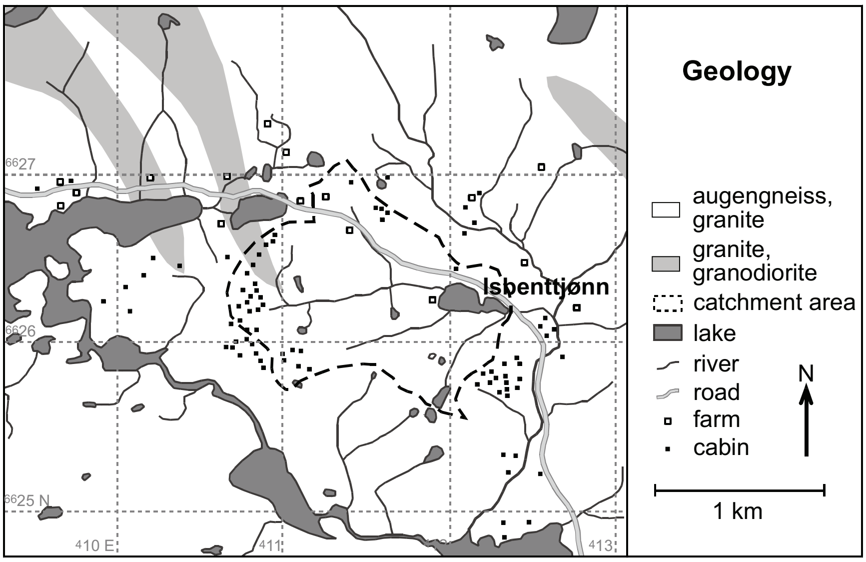


Figure 2.10: Geological map of the area around Isbenttjønn. Source: *modified from Norges Geologiske Undersøkelse (2006).*

Isbenttjønn is located in the upper part of the northern boreal vegetation zone. The lake is surrounded by open birch forest with scattered pines. On the north-facing slope, the forest is dry with *Juniperus communis*, *Salix lapponum*, *Calluna vulgaris*, *Vaccinium uliginosum*, *Deschampsia flexuosa*, *Solidago virgaurea*, *Polygonum viviparum*, *Melampyrum pratense*, and *Molinia caerulea* being present. Here, areas of bare rock can be seen. On the west of the lake, birch forest has developed on a moister area with *Betula nana*, *Eriophorum vaginatum*, *Vaccinium uliginosum*, *Carex bigelowii*, *Nardus stricta*, *Deschampsia flexuosa*, *Potentilla erecta*, *Trichophorum cespitosum*, and *Molinia cearulea*. In the north-western corner of the lake, a bog dominated by *Sphagnum*, with *Salix lapponum*, *Andromeda polifolia*, *Carex limosa*, *C. magellanica*, *C. nigra*, *C. pauciflora*, *Juncus filiformis*, *Viola palustris*, and *Rubus chamaemorus* has developed. Macrophytes like *Sparganium angustifolium* and *Carex rostrata* are found in the lake.

There are several old huts located on the western shore of Isbenttjønn (no. 1, *Fig. 2.9*). They were used as alpine pasture huts (støl) during the last centuries (U. Høydal 2006, pers. comm.). In the area around these 'støls', the vegetation is dominated by *Deschampsia flexuosa*, *Festuca rubra*, and *Carex nigra*. In former times, the whole area around Isbenttjønn was used for pasture by cows and goats, while sheep pastures were located at higher altitudes. Between 1920 and 1930, the 'støls' at Isbenttjønn were extended to small farms. Pasturing ended in the 1950s and from that time on, the huts have been used for recreational purposes (U. Høydal 2006, pers.

comm.). The huts along the road at the western margin of the drainage area (no. 2; *Fig. 2.9*) were built only c. 30 years ago and are used for recreational purposes (U. Høydal 2006, pers. comm.).

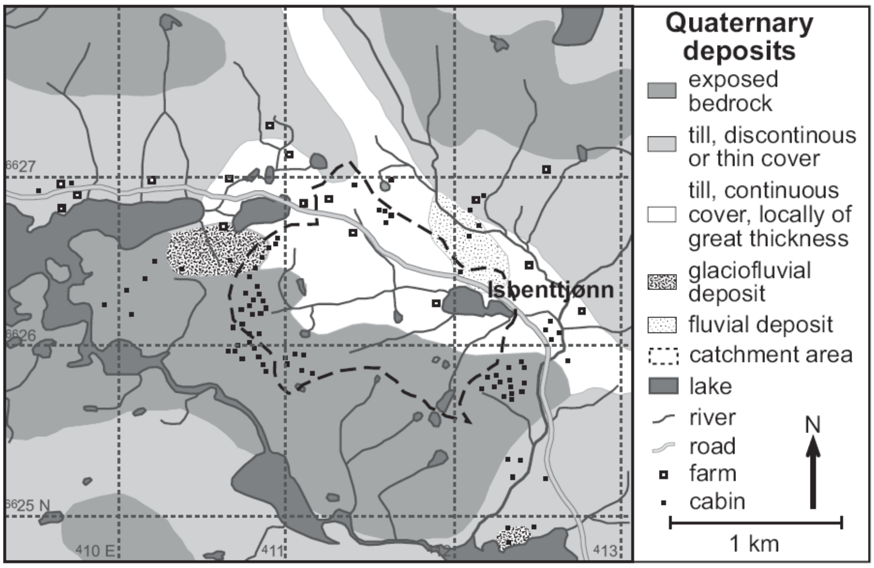


Figure 2.11: The Quaternary sediments in the area around Isbenttjønn. Source: *modified from Norges Geologiske Undersøkelse (2006).*

Chapter 3: Methods

Coring and sampling

Sediment cores were recovered in 1996 (Isbenttjønn) and 1997 (Reiarsdalsvatnet) by H.J.B. Birks and members of the Botanical Institute, University of Bergen, and of the Environmental Change Research Centre, University College London. A 5 cm diameter modified Livingstone piston corer (Wright 1967) was used to take two series of overlapping sediment cores from each lake. To obtain undisturbed sediment from the sediment-water interface, a modified Kajak gravity corer was used (Renberg 1991). The unconsolidated sediment retrieved by the gravity corer was extruded in the field and cut into 1 cm slices. These samples and the other cores were stored at 4°C until subsampling. Overlapping sediment segments were correlated using loss-on-ignition data and depth, resulting in a 385 cm long master sequence for Reiarsdalsvatnet and a 260 cm long one for Isbenttjønn.

Dating, age-depth modelling, and sedimentation rates

Small bulk sediment samples were dated from sediment slices of 0.5 cm to 1.5 cm thickness. The Accelerator Mass Spectrometry (AMS) radiocarbon dating of the bulk organic matter was carried out at the Radiocarbon Dating Laboratory in Trondheim, Norway in 1998 and 1999. The uncalibrated data were provided by H.J.B. Birks to be used in this study. Calibrations were obtained applying the IntCal04 calibration (Reimer *et al.* 2004) and the programme CALIB 5.0.1 (Stuiver and Reimer 1993, Stuiver and Reimer 2005). Age-depth modelling was performed following Heegaard *et al.* (2005), applying a generalised mixed-effect regression procedure with a cubic smooth spline function and the statistical software R (The R development Core Team 2005). The surface sample was fixed to 1996 and 1997, respectively.

After setting up the chronology for the sediment profiles, sedimentation rates (SR, given in cm a^{-1}) were determined by division of the thickness in cm of a sediment slice (1 cm) by the number of years in the respective slice. The latter was calculated from the ages determined by the age-depth model for every centimetre of the profile.

Physical and chemical proxy data

Water content, bulk- and dry density, loss-on-ignition

Analyses of water content (WC), bulk density (BD), and loss-on-ignition at 550°C (LOI) were carried out at the Botanical Institute, University of Bergen. Subsamples of 1 cm^3 were analysed at 2 to 4 cm intervals for Reiarsdalsvatnet and at 1 cm intervals for Isbenttjønn, resulting in a total of 92 and 215 samples, respectively. WC, BD, dry density (DD) and LOI were determined according to Bengtsson and Enell (1986) and calculated as follows:

$$\text{WC}\ [\text{wt.\%}] = (\text{FW}\ [\text{g}] - \text{DW}\ [\text{g}]) * (\text{FW}\ [\text{g}])^{-1} * 100 \qquad \text{(equation 1)}$$

$$\text{BD}\ [\text{g cm}^{-3}] = \text{FW}\ [\text{g}] * (\text{V}\ [\text{cm}^{3}])^{-1} \qquad \text{(equation 2)}$$

$$\text{DD}\ [\text{g cm}^{-3}] = (\text{BD}\ [\text{g cm}^{-3}] * 100^{-1}) * (100 - \text{WC}\ [\text{wt.\%}]) \qquad \text{(equation 3)}$$

$$\text{LOI}\ [\text{wt.\%}] = (\text{DW}\ [\text{g}] - \text{AW}\ [\text{g}]) * (\text{DW}\ [\text{g}])^{-1} * 100 \qquad \text{(equation 4)}$$

where DW: weight of sample after drying at 105°C, FW: weight of fresh sample, V: volume of fresh sample, AW: weight of ash after ignition of the sample at 550°C.

Total carbon, nitrogen and sulphur

97 samples were analysed for total carbon (TC), total nitrogen (TN), and total sulphur (TS) all given in weight percent (wt.-%) at the laboratory of Geopolar, University of Bremen. Prior to the analysis, sediment samples were freeze-dried and homogenised. Analyses were conducted with a EuroEA elemental analyser (Eurovector). In the process, samples are fully oxygenised by combustion at 1800°C, gases are split chromatographically, and determined by thermal conductivity. Tests with hydrochloric acid showed that sediment from Reiarsdalsvatnet and Isbenttjønn contain no carbonate. Thus it is imperative that

$$\text{TC} = \text{TOC} \qquad \text{(equation 5)}$$

where TC: total carbon and TOC: total organic carbon. Hereafter, TC is referred to as TOC. TOC:TN and TOC:TS weight ratios (hereafter C:N and C:S, respectively) were determined to characterise the organic matter in the sediment (cf. Hansen 1959, Meyers and Teranes 2001, Nriagu and Soon 1985).

Biogenic silica

For the profile Isbenttjønn, biogenic silica (BSi) was determined by continuous flow analysis (Müller and Schneider 1993) at the laboratory of Geopolar, University of Bremen. The method is based on the different solution of minerogenic and biogenic silica. Because biogenic silica is amorphous, it is dissolved quickly, in contrast to slowly dissolving minerogenic silica. This difference is recorded by the applied continuous flow procedure. Sediment samples were freeze-dried and homogenised prior to analysis. Biogenic silica was dissolved with sodium hydroxide at 85°C. Sulphuric acid, molybdate, oxalic acid and ascorbic acid were added to a continuously taken sub-sample of the solution, which undergoes a reaction forming a molybdenum blue complex. The resulting hue of blue is correlated to the amount of dissolved silica and is measured continuously with a photometer. The amount of biogenic silica was then determined by the subtraction of minerogenic silica from total dissolved silica.

Biological proxy data

Pollen

Pollen analyses were carried out by S.M. Peglar at the Botanical Institute, University of Bergen. For these analyses, 0.5 cm³ subsamples were taken at 4 cm intervals at both profiles, with smaller intervals of 2 cm at the bottom of the cores. They were treated by standard Method B of Berglund and Ralska-Jasiewiczowa (1986) and suspended in silicone oil. Pollen was counted at x 400 magnification. Larger magnification (x 1000) was used for critical examinations. Identification to the lowest possible taxonomic level is based on keys (Birks 1973, Moore *et al.* 1991) and an extensive pollen reference collection at the Botanical Institute, University of Bergen. A minimum of 500 terrestrial pollen grains and spores per sample were counted. According to Birks (1973), after sieving, the coarse fraction (>100 µm) of the pollen samples was examined microscopically at lower magnification and the components were identified. The relative proportions of the categories ‘Sand’, ‘Large detritus’, ‘Small detritus’, ‘Oribatid mites’, ‘Other Cladocera’, ‘Other animal remains’ and ‘Charcoal particles’ were estimated visually on a 5-point scale (absent, rare, occasional, frequent, abundant). The categories ‘*Juncus* seeds’, ‘*Pinus* budscales’, ‘*Sphagnum* leaves’, ‘Other mosses’, ‘*Daphnia* ephippia’, ‘*Plumatella* statoblasts’, and ‘Nymphaeaceae 'star' cells’ are given as counts. This data are hereafter referred to as ‘coarse fraction’ or ‘macroscopic’.

Subfossil chironomid remains

Subsamples were taken at 8 to 2 cm intervals for the analysis of subfossil chironomid remains. Samples of Reiarsdalsvatnet were fresh, while freeze-dried material was used from Isbenttjønn. Both fresh and freeze-dried sediment samples were processed following Walker (2001), using 8 % KOH for deflocculation and a 100 µm sieve. Due to the organic nature of the sediment and the lack of calcareous material, treatment with HCl and HF was omitted. After hand-picking of chironomid head-capsules from the processed sediment under x 40 magnification and dehydration of the head-capsules in 96 % alcohol, the head-capsules were mounted in Canada Balsam on microscopic slides. For the calculations, head-capsule fragments were counted as one head-capsule if more than half part of the mentum was found, as 0.5 head-capsules if it was half of the mentum, and they were discarded if the remains comprised less than half. Identification under 400 x magnification is based on keys, on the reference collection at the Natural History Museum, London, UK (S.J. Brooks 2002, pers. com.), and on the taxonomy of the Norwegian calibration data-set (Brooks and Birks 2000, 2001, S.J. Brooks and H.J.B. Birks, unpublished data). It has been shown by several studies that a minimum of 50 head-capsules per sample has to be examined to give reliable reconstructions (Heiri and Lotter 2001, Larocque 2001, Quinlan and Smol 2001). For this study, identification of 70 head-capsules per sample was selected as a compromise between reliability of the reconstructions and the time needed for sediment processing and analysis.

Chironomid taxonomy in general is mainly based on diagnostic characters of male adults and pupae, while subfossil material contains mainly larval head-capsules or parts of those. Thus the taxonomic resolution of studies based on subfossil material is always coarser than the one based on recent material. Still, in palaeoecological studies, close approximation to the modern taxonomy is intended to make ecological inferences from subfossil assemblages possible. Most subfossil specimens can be identified to generic level, some even to species level. In the following, '-type' is added to the species name to clarify that the specimen identified is assigned to the morphotype of the species larvae. 'Spp.' is added if specimen can only be identified to genus level, even though other specimen of this genus can be identified to species level. Identification details for each taxon are given in *Table A1*. Most taxa were identified using the descriptions in Wiederholm (1983), Heiri *et al.* (2004a), and Rieradevall and Brooks (2001). Single types were identified following Brooks *et al.* (1997), Cranston (1982), Hirvenoja (1973), Hofmann (1971), Oliver and Roussel (1983), Rieradevall (1999), Schmid (1993) and Sæther (1975a). In four cases, the taxonomic types of the Norwegian calibration data-set were changed due to taxonomic uncertainties and the fact that in some taxa, the teeth of the mentums were worn:

- Corynoneura scutellata and C. edwarsii were merged to form C. scutellata-type,
- Cricotopus sp C and C. sp D were merged to form C. sp CD,
- *C. sp E* and *C. sylvestris* were merged to form *C. sylvestris*-type, and
- Georthocladius and Parachaetocladius were merged to form Georthocladius/ Parachaetocladius-type.

For Isbenttjønn non-chironomid remains were identified in addition to chironomids, following descriptions in Uutala (1990) for *Chaoborus*, Szadziewski *et al.* (1997) for Ceratopogonidae, Engblom (1996) for Ephemeroptera, Brittain and Saltveit (1996) for Plecoptera, Carlsson (1962), Davies (1968) and Jensen (1997) for Simuliidae, and Sedlák (1985) for Trichoptera.

Autecological information about chironomid taxa is very heterogenic, often sparse and only available at the species level. This makes the information not directly applicable to subfossil taxa, which can often only be identified to genus level. To be able to obtain qualitative ecological information from subfossil data, the following approach was chosen:

All species, which might possibly be included in the subfossil taxa, were determined from the Norwegian chironomid taxa inventory list (Schnell and Aargaard 1996), (*Tab. A2*). Species present in any of the counties in Southern Norway were regarded as possibly present in Reiarsdalsvatnet and Isbenttjønn. Information about trophic preferences of these species was derived from Sæther (1979). Chironomids were categorised as 'oligotrophic', 'mesotrophic', 'eutrophic', and 'humic' according to the central point of their distribution (Table 2 in Sæther 1979), (*Tab. A2*). A comparison of the data from Sæther (1979) with results of different modern calibration data-sets linking chironomid assemblages to lake productivity indicators such as total phosphorous or chlorophyll-a (Brodersen and Anderson 2002, Brodersen and Lindegaard 1999, Brooks *et al.* 2001, Lotter *et al.* 1998) showed that there is an overall agreement in the ranking of species optima (Brodersen and Quinlan 2006). Information about feeding habits and habitats was compiled from Moog (2002). Even though the study of Moog (2002) focuses on lotic communities, valuable information about chironomids preferring lentic habitats is also given. To account for the lotic focus of these data, for the present study chironomid habitats were categorised as 'lotic' only, when the sum of lotic habitats in Moog (2002) was 6 or larger. In all other cases, the species were categorised as 'littoral' or 'profundal', according to the maximum in the respective category in Moog (2002), (*Tab. A2*). The functional feeding groups of Moog (2002) follow the categories defined in Cummins and Merrit (1984), (*Tab. A2*). The ecological information about the chironomid species was then combined for the subfossil taxa (*Tab. A2*). If the species belonging to one subfossil taxon group did not have a definite ecological preference, all recorded preferences are ascribed to the subfossil taxon. After this categorisation, the percentage values and influx values, respectively, of all taxa belonging to one category (e.g., 'lotic'), were aggregated to form the 'lotic % index' or 'lotic IF index'. Since taxa may belong to multiple categories or may not be ascribed to any category, the values of the indices do not sum up to 100 %.

Numerical data analysis

Percentages and influx rates

LOI, TOC, TN, TS, and BSi are given as weight percentages [wt.%] and as influx (IF_{LOI}, IF_{TOC}, etc.). Influx (IF) and specific influx (IF_X) for sediment components (X) were calculated as follows (DD: dry density, SR: sedimentation rate and X: weight percent value of specific sediment component):

$$IF\ [g\ cm^{-2}\ a^{-1}] = DD\ [g\ cm^{-3}] * SR\ [cm\ a^{-1}] \qquad \text{(equation 6)}$$

$$IF_X\ [g\ cm^{-2}\ a^{-1}] = IF\ [g\ cm^{-2}\ a^{-1}] * X\ [wt.\%] * 10^{-2} \qquad \text{(equation 7)}$$

Pollen and chironomid data are presented as percentages of the total sum of terrestrial pollen and chironomid head-capsules of a sample, respectively. Percentages of aquatic pollen/spores, *Sphagnum* and microscopic charcoal are calculated using the total sum of terrestrial pollen plus the number of aquatics, *Sphagnum* or charcoal as calculation sum (i.e., 100 %). Percentages of non-chironomid remains are calculated in the same manner, with the number of chironomid head-capsules and of non-chironomid remains in one sample adding up to 100 %. Influx of chironomid head-capsules (IF_{hc}), were determined according to:

$$IF_{hc}\ [\text{counts m}^{-2}\ \text{a}^{-1}] = IF\ [\text{g m}^{-2}\ \text{a}^{-1}] * hc\ [\text{counts}] * (DW\ [\text{g}])^{-1} \qquad \text{(equation 8)}$$

where IF: influx, hc: number of chironomid head-capsules, DW: weight of sample after drying at 105°C.

Initially, head-capsule influx of the Reiarsdalsvatnet profile was determined by means of adding microspheres to the sample material during the separation of head-capsules from the sediment. Since this procedure resulted in considerably higher influx rates compared to the influx calculations based on the separation of all head-capsules from the weighed sediment samples, they were omitted (cf. Chapter 5). Influx of pollen was not determined, since this study focuses on chironomid analyses.

Ordination

For all ordinations, percentage pollen and chironomid data were square-root transformed in an attempt to stabilise the variance in each data-set. Detrended correspondence analysis (DCA, Hill and Gauch 1980) with down-weighted rare species and detrending-by-segments was used for a first exploration of the taxonomic variation in the data-sets. DCA axis 1 sample scores are given in standard deviation units (SD) and express the amount of compositional change between samples, i.e., the extent of species turnover or beta diversity in assemblage composition (Lepš and Šmilauer 2003). Since DCA gradient lengths were shorter than 2 SD for the pollen and chironomid data-sets of both lakes, the linear method principal component analysis (PCA) was chosen as appropriate method to summarise the major trends in the data-sets (Lepš and Šmilauer 2003). The statistical significance of the first four PCA axes was assessed by comparison with the broken-stick model (Bennett 1996). All ordinations were performed using the software CANOCO version 4.5 (ter Braak and Šmilauer 2002a, ter Braak and Šmilauer 2002b).

Rate-of-change analysis

Rates of change were calculated to estimate the amount of change per unit of time (Grimm and Jacobson 1992, Lotter *et al.* 1992). Dissimilarities between samples are expressed as chord distances (chord dissimilarity coefficient – DC) for standard time units of 150 calibrated radiocarbon years and are calculated for pollen and chironomid percentage data. Computation was done using the programme RATEPOL version 0.8 (Line and Birks unpublished). In the first step, no interpolation or smoothing procedures were applied. In a second step, linear interpolation (150 years time intervals) but no smoothing was used to account for the effects of different sample densities in the data-sets. Permutation tests (999 permutations) were carried out to identify the rates of change, which are greater than they would be expected by chance, given the initial sampling resolution and the inherent variance of each data-set. Rates of change greater than the 95 percentile of the permutation test are regarded as being significant (Birks *et al.* 2000).

Temperature reconstructions

Both pollen and chironomid-inferred temperature reconstructions in this study are based on weighted averaging partial least squares (WA-PLS) models (ter Braak and Juggins 1993). WA-PLS is a multivariate indicator species approach (Birks 2003), where all taxa are included in the transfer function. The optima of the taxa are not derived from autecological observations, but are modelled from the modern calibration data-set (Birks 2003). WA-PLS is a simple and robust approach for quantitative palaeoenvironmental reconstruction and performs well with noisy, species-rich data with many zero values (Birks 1995, 1998, 2003). The WA-PLS model was established using square-root transformed percentages of species data and the programme C2 version 1.4.2 (Juggins 2003).

Pollen-based reconstructions of mean July air temperatures were carried out using a 190-lakes pollen calibration data-set covering a large temperature gradient (Birks and Seppä 2004, Seppä and Birks 2001, H.J.B. Birks and S.M. Peglar, unpublished data). The data-set includes 163 lakes from Norway spanning the full north-south gradient, but excluding Svalbard, and 27 lakes from northern Sweden. Modern temperatures and precipitation for the lakes are modelled from nearby meteorological stations using mean values of the 1961 – 1990 normal period and corrected for lapse rates (A. Odland, unpublished data). For reconstruction of chironomid-inferred mean July air temperatures, the Norwegian chironomid calibration data-set extending from Svalbard (80°N) to southern Norway (58 °N) was used (Brooks and Birks 2000, 2001, S.J. Brooks and H.J.B. Birks, unpublished data). This data-set comprises modern chironomid assemblage data from surface sediment samples of 153 Norwegian lakes, modern lake chemistry data, temperature means and mean precipitation sums for the respective lakes. Modern climate data for the lakes were derived from the nearest meteorological stations as described above (Brooks and Birks 2001, A. Odland, unpublished data).

The performance of the WA-PLS model calculated by leave-one-out cross-validation (ter Braak and Juggins 1993) is reported in *Table 3.1*. The minimal adequate WA-PLS model was chosen based on a low prediction error (RMSEP), low mean and maximum bias (Birks 1995, 2003), the smallest number of 'useful' components (Birks 1998), and the performance of the model the upper end of the gradient. A two-component WA-PLS model was selected for pollen-based, a three-component WA-PLS model for chironomid-based mean July air temperature reconstruction.

Table 3.1: Performance statistics for the first four components of the weighted averaging partial least squares (WA-PLS) regression models for the Norwegian pollen and chironomid calibration data-sets. RMSEP: root mean squared error of prediction.

	r^2	Average bias [°C]	Maximum bias [°C]	RMSEP [°C]
WA-PLS pollen				
Component 1	0.502	0.042	3.960	1.071
Component 2	0.534	0.000	3.679	1.038
Component 3	0.543	0.021	3.533	1.030
Component 4	0.530	0.010	3.257	1.064
WAPLS chironomids				
Component 1	0.819	0.043	1.933	1.506
Component 2	0.900	0.003	1.108	1.087
Component 3	0.912	-0.009	1.171	1.019
Component 4	0.907	-0.024	0.972	1.053

Samples with a chironomid count sum below 50 head-capsules were omitted for the reconstructions because of statistical unreliabilities (Heiri and Lotter 2001, Larocque 2001, Quinlan and Smol 2001). In addition to the determination of the sample-specific RMSEP, pollen and chironomid-inferred temperature reconstructions were evaluated using the following numerical criteria:

- Modern analogues were determined using modern analogue techniques (Overpeck *et al.* 1985) and the programme C2 version 1.4.2 (Juggins 2003) with chi-square distance as dissimilarity value. This is done to detect down-core samples that lack good modern analogues in the calibration data-set (Birks 1995). The assumption is that the reconstructed temperature is likely to be less reliable, if the assemblage in the down-core sample does not have close modern analogues in the modern calibration data-set (ter Braak 1995).
- 'Goodness-of-fit' statistics (Birks 1995, Birks *et al.* 1990) are based on the idea of fitting the down-core samples passively to a canonical correspondence analysis (CCA) of the modern calibration data, which is constrained to the observed mean July temperatures (Birks *et al.* 1990). Down-core samples with a large squared residual distance to the first axis are considered as having a 'poor fit'.

- The percentage of total fossil assemblage that consists of taxa that are present is the modern calibration data (Birks 1998) is calculated for each down-core sample. Since taxa present in the down-core samples but not in the modern calibration data do not influence the temperature reconstructions, a distinct amount of information is lost when the percentage of these taxa in the fossil assemblage is large.

The century-scale temporal trends of the reconstructed temperatures are highlighted by a smoothing function. Here, a locally weighted scatter plot smooth (LOWESS, span = 0.1), (Legendre and Legendre 1998) is used.

Graphs and Zonation

Diagrams of geochemical, pollen, and chironomid data were drawn with the programme C2 1.4.2 (Juggins 2003). The zonation of sedimentological and geochemical data was done together for all proxies, based on visual examination of the profiles. Local chironomid and pollen assemblage zones were defined based on the percentage data of the respective proxy. The zonation was done by optimal sum of squares partitioning and unweighted least squares analysis (SLITLSQ), (Birks and Gordon 1985) in the programme ZONE (Juggins 1991). The number of statistical significant assemblage zones was assessed by comparison with the broken-stick model (Bennett 1996). If a significant zone contained only one sample, it was merged with the consecutive zone.

Chapter 4: Catchment histories and sedimentary changes

Introduction

Since the vigorous scientific discussion in the 1990's as to whether temperature or other local variables are most influential on chironomid assemblages (Hann *et al.* 1992, Walker *et al.* 1992, Walker *et al.* 1991b, Warner and Hann 1987), it has been shown in many studies that the most important environmental variable explaining the broad-scale geographical distribution and abundance of chironomid taxa is temperature (e.g. Lotter *et al.* 1997, Olander *et al.* 1999, Walker *et al.* 1997). Walker *et al.* (1997) emphasise the importance of scale in this context by stating that 'if we were to expand our (*modern calibration, B.L.*) database to include lakes spanning an even greater climatic range, the influence of climate can be expected to explain an increasing proportion of the variance (*in the chironomid assemblages, B.L.*). If the scale were contracted to the point where all the lakes studied received the same thermal input, (…) depth and other local factors, together with biotic processes, would assume inevitably dominance' (Walker *et al.* 1992). If this idea is transferred from the spatial to the temporal scale, local factors should play a minor role when reconstructing large temperature gradients, i.e., large temperature changes such as they occurred during the Late Glacial. During time periods with a short temperature gradient such as the Holocene, chironomid assemblages are more likely to be affected by local factors. Thus the optimal system to reconstruct small-scale temperature changes based on the analysis of chironomid remains would be a lake with stable local factors during the studied time period.

Since lakes are natural systems, they are always influenced by local factors and change through time. Thus it is necessary to choose sites that are thought a priori to have undergone as little change as possible during the respective time period. In addition, local changes have to be reconstructed independently from proxy-data other than chironomid remains. This opens the possibility to differentiate periods where local factors may have played a major role on the chironomid assemblages from periods where the lake was stable with regard to these factors. For this purpose, a multi-proxy approach was adopted to study the non-alpine lakes Reiarsdalsvatnet and Isbenttjønn. The catchments of both lakes have been forested throughout most of the Holocene and it is hypothesised that during the Holocene the lake systems were stable and that only minor changes in the lakes' sedimentation processes occurred. The aim of this Chapter is to set up a framework for the chironomid studies by reconstructing the ecological development of the lakes and their catchments with chironomid-independent data. This will be achieved by the establishment of a chronology for the lake sediment profiles and by the interpretation of site and sediment descriptions, as well as pollen and geochemical data.

The specific questions to be answered in this Chapter are:

- How did the lakes originate and when did they start to exist?
- How did the trophic state of the lakes change during the Holocene?
- How did the local vegetation develop during the Holocene?
- Did human activity influence the lakes or their catchments?

Results

Lithology

Reiarsdalsvatnet

The 385 cm long sediment core from Reiarsdalsvatnet (RV) is structured in two macroscopically visible units: Clastic material in the lower part (< 336 cm) and organic sediments in the upper and main part (*Fig. 4.1*). Gravel and coarse sand is found below 348 cm with a band of clay and finer sand from 367 cm to 376 cm. Above 348 cm, bands of clay and sand are seen up to 336 cm sediment depth, where a very sharp boundary divides the clastic from the organic sediment.

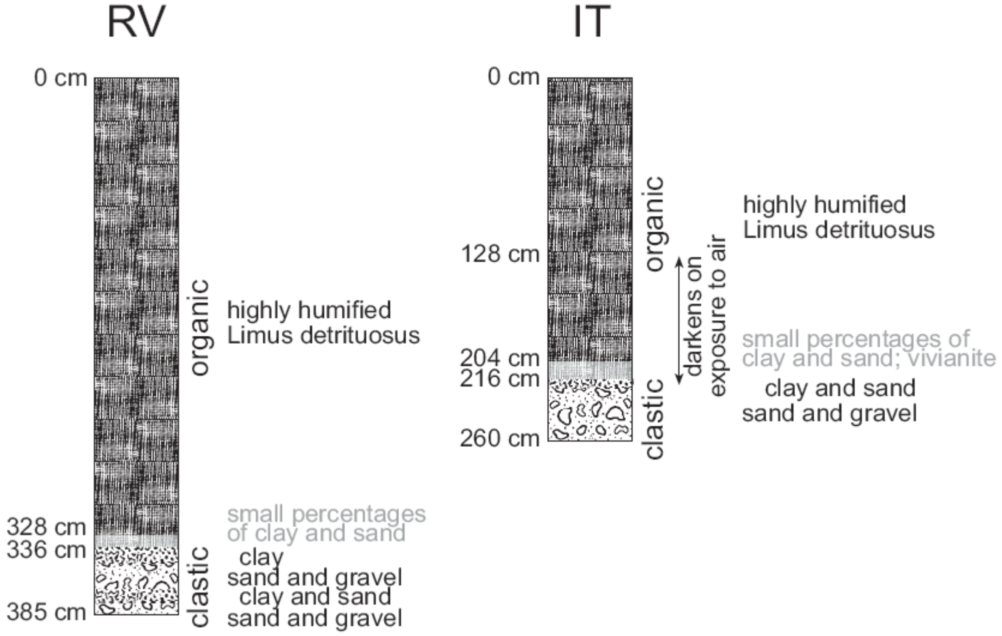


Figure 4.1: Lithologies of the composite sediment profiles from Reiarsdalsvatnet (RV) and Isbenttjønn (IT).

According to the sediment description scheme of Troels-Smith (1955), the organic-rich, non-calcareous sediment is highly humified Limus detrituosus with traces of plant fragments. It constitutes the main part of the profile above 336 cm. Only in the oldest part of the organic sediment (from 336 cm to 328 cm) are small percentages of sand and clay present. Since this study focuses on biological proxies, only a few subsamples were taken from 336 cm to 346 cm and no subsamples were taken below 346 cm.

Isbenttjønn

The sediment core from Isbenttjønn (IT) is 260 cm long and is structured into an older part of clastic sediments, and the main upper part of organic material (*Fig. 4.1*). Below 215 cm, the sediment consists of gravel and sand. Only in the uppermost centimetre of this unit, finer fractions (sandy clay) are found. No subsamples were taken below 216 cm. Above 215 cm, the sediment is non-calcareous, highly humified Limus

Table 4.1: Summary of the AMS radiocarbon dates for Reiarsdalsvatnet and Isbenttjønn (Radiocarbon Dating Laboratory, Trondheim, Norway) and their calibration using the IntCal04 calibration (Reimer et al. *2004) and the programme CALIB 5.0.1 (Stuiver and Reimer 1993, Stuiver and Reimer 2005).*

Lake	Sample	Laboratory number	Sample depth [cm]		AMS^{14}C age [BP]		Central 68% percentage range of the probability distribution of the calibrated ^{14}C dates			
							range [cal. BP]		relative	mid-point
			from	to		± 1 sd	from	to	area	[cal. BP]
Reiarsdalsvatnet	R 898	Tua-2362A	63.5	64	**825**	60	685	787	1	**736**
Reiarsdalsvatnet	R 946	Tua-2363A	111.5	112	**1385**	60	1265	1353	1	**1309**
Reiarsdalsvatnet	R 970	Tua-2364A	135.5	136	**2070**	60	1951	1960	0.051902	**2035.5**
							1970	1979	0.045074	
							1986	2120	0.903024	
Reiarsdalsvatnet	R 998	Tua-2365A	163.5	164	**2690**	60	2755	2845	1	**2800**
Reiarsdalsvatnet	R 1053	Tua-2366A	218.5	219	**3540**	60	3721	3800	0.460216	**3810**
							3811	3899	0.539784	
Reiarsdalsvatnet	R 1099.5	Tua-2367A	265	265.5	**6365**	55	7252	7332	0.727639	**7333.5**
							7355	7373	0.105975	
							7389	7415	0.166385	
Reiarsdalsvatnet	R 1153.5	Tua-2368A	318.5	319.5	**7805**	70	8456	8499	0.155816	**8569**
							8507	8647	0.828748	
							8677	8682	0.015436	
Reiarsdalsvatnet	R 1169.5	TUa-2369A	334.5	335.5	**9415**	65	10568	10728	1	**10648**
Isbenttjønn	I 954	TUa-1975A	17	18	**1860**	65	1722	1869	1	**1795.5**
Isbenttjønn	I 992	TUa-1976A	55.5	56	**2130**	70	2000	2158	0.807634	**2149.5**
							2255	2299	0.192366	
Isbenttjønn	I 1036	TUa-1977A	99.5	1000	**2995**	55	3078	3095	0.082339	**3197.5**
							3102	3132	0.141567	
							3136	3263	0.741724	
							3309	3317	0.034369	
Isbenttjønn	I 1084	TUa-1978A	147.5	1048	**4705**	70	5324	5416	0.554719	**5450.5**
							5443	5478	0.21037	
							5536	5577	0.234911	
Isbenttjønn	I 1128	TUa-1979A	191.5	192	**6270**	85	7024	7118	0.327377	**7149**
							7153	7274	0.672623	
Isbenttjønn	I 1136	TUa-1980A	199.5	200	**7240**	60	7998	8061	0.49528	**8078**
							8087	8158	0.50472	
Isbenttjønn	I 1152	TUa-1981A	214.5	216	**9265**	55	10300	10318	0.080676	**10427**
							10345	10346	0.003943	
							10380	10523	0.823837	
							10532	10554	0.091544	

detrituosus with traces of plant fragments (Troels-Smith 1955). In a transition zone from 215 cm to 204 cm, clastic material (sand and clay) is present in low amounts in the organic sediment and vivianite occurs. The sediment below 128 cm shows some evidence of iron staining which disappear on exposure to air.

Chronology, sedimentation rates, and sample resolution

The chronologies of the Reiarsdalsvatnet and the Isbenttjønn profiles are based on 8 and 6 AMS^{14}C dates from bulk organic matter, respectively (*Tab. 4.1*). Generally, radiocarbon dates obtained from bulk sediment have to be interpreted carefully. As demonstrated by several studies, reservoir effects do not only occur in hard water-lakes, but radiocarbon dates from bulk sediment of soft water lakes can as well show an offset of 100 to 500 years compared to varve counting or radiocarbon dating of terrestrial macrofossils (Björck *et al.* 1998, Oldfield *et al.* 1997). Even though dating of terrestrial macrofossils would have been preferable to dating of bulk organic matter, this was not possible in the present study since the dating of the cores was already done in 1998 and 1999 and additional means for dating were not available. In both lakes, no material from the oldest, clastic parts of the profiles was dated. The age-depth models were extrapolated for the sub-samples older than the oldest radiocarbon dates. Since sedimentation rates in the clastic part of the profile are expected to be different to the ones of the organic sediment, the extrapolated ages for the clastic sub-samples can only be rough estimates.

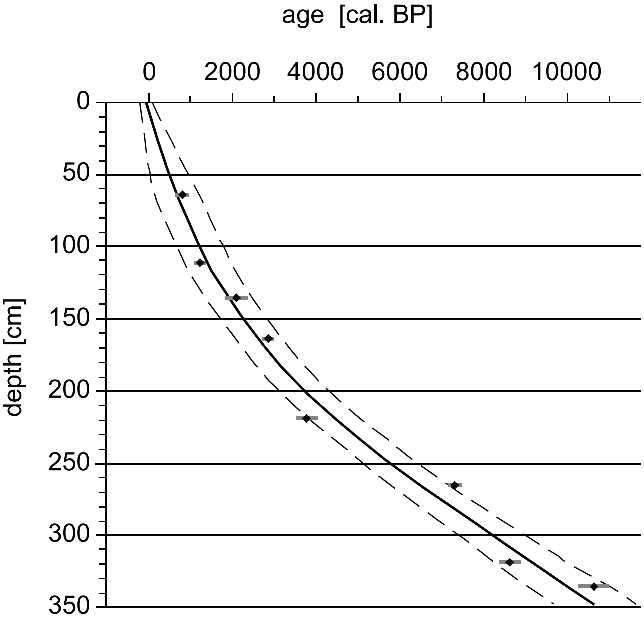


Figure 4.2: Age-depth model for the Reiarsdalsvatnet profile including 95 % confidence intervals (dashed lines), and the calibrated radiocarbon dates (diamonds) with error bars (grey; 95 % confidence intervals).

Reiarsdalsvatnet

For the Reiarsdalsvatnet profile, no age reversals occur and none of the probability distributions of the calibrated radiocarbon dates overlap (*Tab. 4.1*). The age-depth model with constant variance and default values (Heegaard *et al.* 2005) was chosen as the minimum adequate model (*Fig. 4.2*). Uncertainties of the modelled ages (expressed as sample specific 95 % confidence intervals) decrease towards the sediment top, from ±990 years at the bottom of the profile to ±150 years for the youngest sediments (*Fig. 4.2*). Sedimentation rates derived from this age-depth model increase with decreasing depths (*Fig. 4.3*) with a mean sedimentation rate of 0.4 mm a^{-1}. Minimum values are found at the bottom of the profile (10,100 cal. BP: 0.2 mm a^{-1}). From c. 4,000 cal. BP, sedimentation rates start to increase distinctly to reach their maximum values (0.9 mm a^{-1}) at the top of the record.

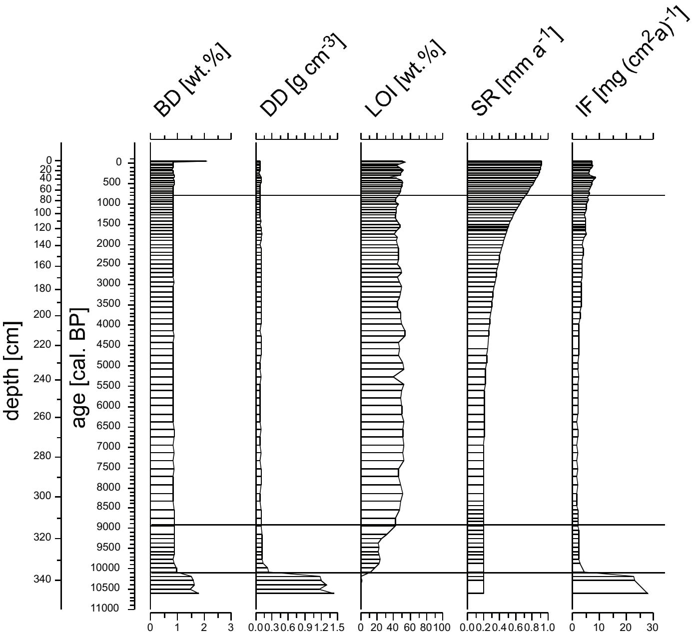


Figure 4.3: Bulk density (BD), dry density (DD), loss-on-ignition (LOI), sedimentation rates (SR), and total influx (IF) for Reiarsdalsvatnet. Sedimentation zones are indicated by solid lines.

Isbenttjønn

The calibrated radiocarbon dates from Isbenttjønn similarly do not show age reversals, but overlap of probability distributions occurs for samples I 954 and I 992. When applying the age-depth model of Heegaard *et al.* (2005) to all the radiocarbon dates with default values and a fixed sediment surface, the resulting age-depth relation is almost linear (*Fig. 4.4*). Regarding the calibrated radiocarbon dates and taking the age-depth relations of comparable lakes into account (e.g. Giesecke 2005, Velle *et al.* 2005a), the linear age-depth relation is not a good description of the sedimentation during the Holocene. It most likely is a statistical artefact or connected to a dating error. To obtain a more realistic model, the following assumptions are made:

- The age-depth relation of Isbenttjønn can generally be described well by the age-depth function of Heegaard *et al.* (2005).
- The sediment surface of the profile was obtained and preserved. If any sediment loss occurred yet, it cannot have exceeded 5 cm (based on the sampling and subsampling protocols of H.J.B. Birks and S.M. Peglar).
- No abrupt sedimentation changes occurred. Neither the macroscopic sediment description, nor the results of the geochemical analyses indicate such discontinuities.

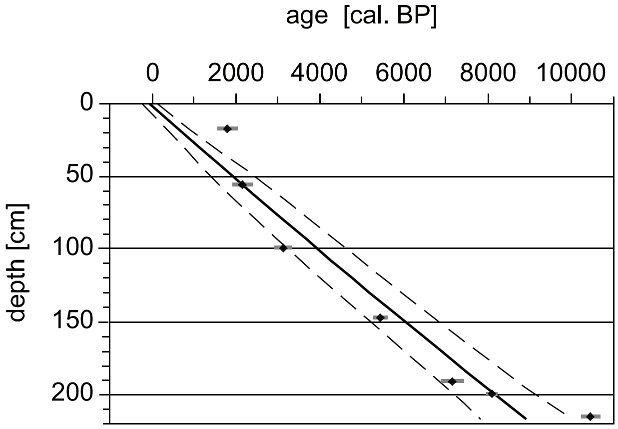


Figure 4.4: Age-depth model for the Isbenttjønn profile based on seven radiocarbon dates including 95 % confidence intervals (dashed lines), and the calibrated radiocarbon dates (diamonds) with error bars (grey; 95 % confidence intervals).

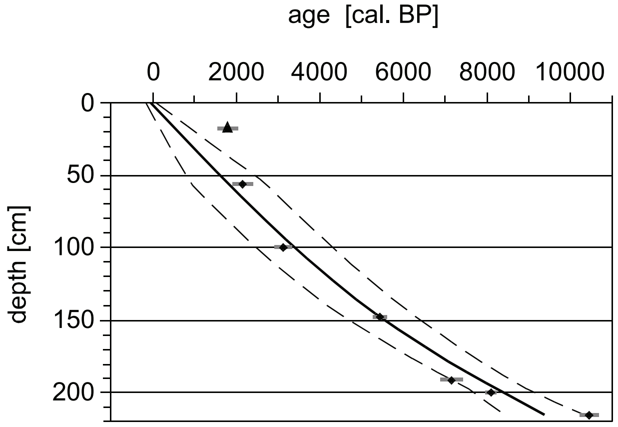


Figure 4.5: Age-depth model for the Isbenttjønn profile based on six radiocarbon dates (excluding sample I 954, triangle), together with 95 % confidence intervals (dashed lines) and the calibrated radiocarbon dates (diamonds) with error bars (grey; 95 % confidence intervals).

With these assumptions, the most parsimonious model is achieved by rejecting the youngest date (I 954) and choosing the age-depth model with constant variance and default values (Heegaard *et al.* 2005), (*Fig. 4.5*). The 95 % confidence intervals of the age-depth model show decreasing variances from ±940 to ±130 years with decreasing sediment depths. Since there is no additional information about sample I 954, it can only be speculated that it contains fractions of old carbon probably derived from soil erosion and thus the radiocarbon age is older than the actual age of deposition. Sedimentation rates of Isbenttjønn (*Fig. 4.6*) show a less distinct increase towards the top compared to those of Reiarsdalsvatnet. Minimum sedimentation rates at the bottom of the profile (9,350 cal. BP: 0.2 mm a^{-1}) are replaced by increasing values after 6,000 cal. BP. Maximal values of 0.3 mm a^{-1} are reached at 1,500 cal. BP and sedimentation rates remain at this level up to the youngest sample.

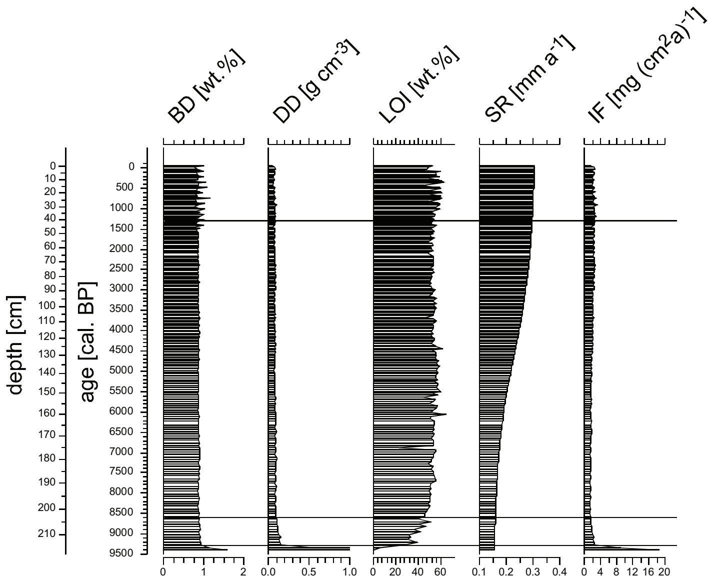


Figure 4.6: Bulk density (BD), dry density (DD), loss-on-ignition (LOI), sedimentation rates (SR), and sediment influx (IF) for Isbenttjønn. Sedimentation zones are indicated by solid lines.

Sample resolution

Taking the sedimentation rates into account, the sample resolution, i.e., the time intervals of two consecutive subsamples, varies between both lakes and for different proxies (*Fig. 4.7, Fig 4.8*). The obvious outliers are either explained by problems in the preparation process or by the fact that not enough material was available for all analyses. For LOI, CNS, and pollen samples of the Reiarsdalsvatnet profile, time resolution varies between 100 and 200 years. Sampling intervals are between 100 and 400 years for chironomid samples. At Isbenttjønn, LOI sample resolution is 60 years, while the resolution of CNS, BSi, pollen, and chironomid samples varies between 130 and 250 years. The number of years in one sub-sample (*Fig. 4.7, Fig 4.8*) is estimated by the number of years contained in one centimetre of sediment. The number decreases from 52 a cm^{-1} at the bottom to 11 a cm^{-1} at the top of the Reiarsdalsvatnet profile, and from 64 a cm^{-1} to 33 a cm^{-1} at the Isbenttjønn profile.

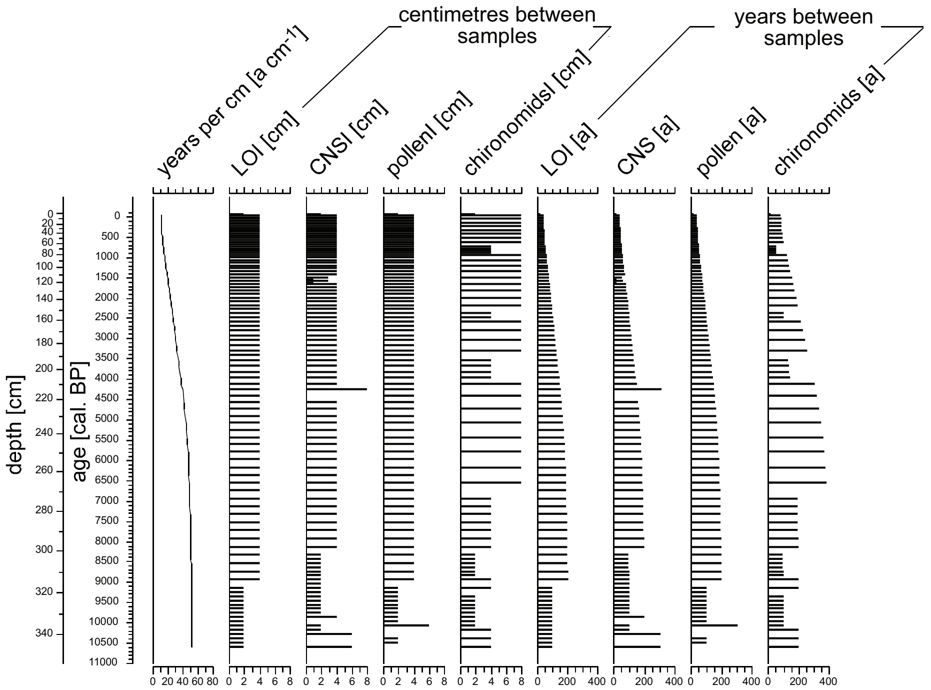


Figure 4.7: Years per centimetre sediment and sample resolutions (centimetres and years between two consecutive samples, respectively) for the different proxies analysed from the sediments of Reiarsdalsvatnet.

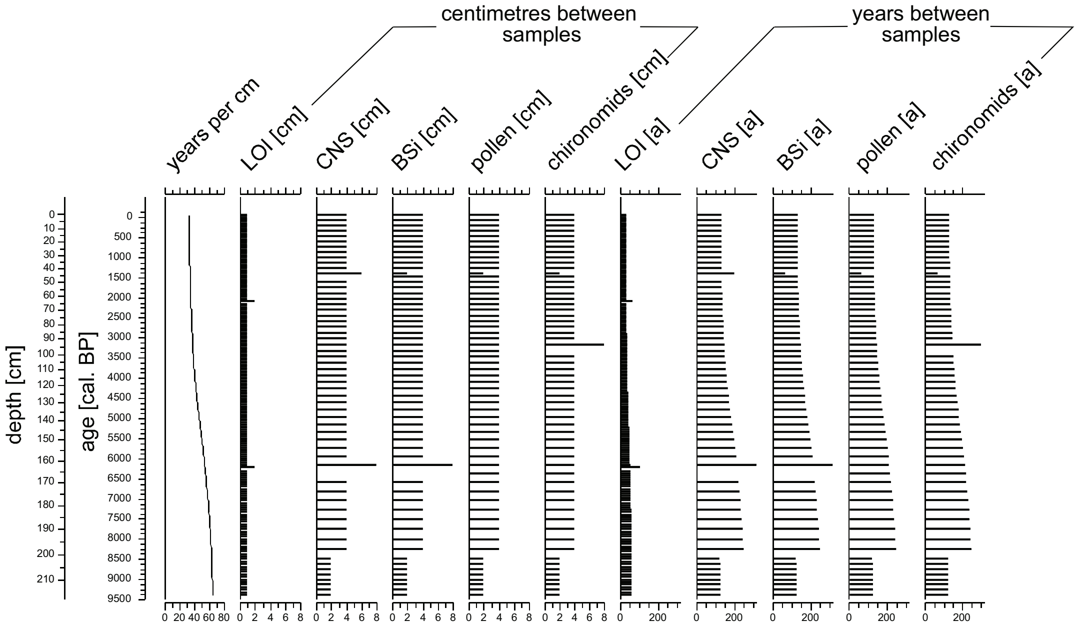


Figure 4.8: Years per centimetre sediment and sample resolutions (centimetres and years between two consecutive samples, respectively) for the different proxies analysed from the sediments of Isbenttjønn.

Dry density and influx rates

The dry density (DD) profiles of Reiarsdalsvatnet (*Fig. 4.3*) and Isbenttjønn (*Fig. 4.6*) mirror the macroscopic sediment description well. Maximum values of 1.4 g cm^{-3} (RV) and 1.2 g cm^{-3} (IT) are determined for the clastic material in the lowest part of the profiles. The organic sediment shows distinctly lower values with means of 0.09 g cm^{-3} in both lakes and minimum values below 0.07 g cm^{-3} in the youngest sediments.

In contrast to the DD values, the minimum influx rates (IF) are not found in the youngest sediments. For Reiarsdalsvatnet, a minimum IF of 1.7 g cm^{-2} a^{-1} is found at 8,350 cal. BP, for Isbenttjønn (1.3 g cm^{-2} a^{-1}) at 7,750 cal. BP. The clastic sediments show maximum IFs (28 g cm^{-2} a^{-1} for both lakes). Mean influx rates for the organic sediment are 3.9 g cm^{-2} a^{-1} (RV) and 2.2 g cm^{-2} a^{-1} (IT), respectively. Apart from general differences between clastic and organic material, DD and IF values show only low fluctuations throughout the sediment profiles of both lakes.

Geochemical data

Reiarsdalsvatnet

In Reiarsdalsvatnet, TN resembles TOC well (*Fig. 4.9*), indicating that the major part of nitrogen is bound organically. The profiles of LOI, TOC, and TN show the onset of the preservation of organic material at 10,100 cal. BP, older samples have very low contents of organic matter (*Fig. 4.3, 4.9*).

From 10,100 cal. BP to 8,950 cal. BP, the LOI, TOC and TN values increase (*Fig. 4.3, 4.9*). This increase takes place in two steps: the first between 10,100 cal. BP and 9,800 cal. BP, the second between 9,400 cal. BP and 8,900 cal. BP. Since 8,900 cal. BP, LOI, TOC and TN are stable with maximum values of 54.2 wt. % LOI, 28.6 wt.% TOC and 2.1 wt. % TN. Slightly increasing contents are detected in the sediment younger than 800 cal. BP. At 350 cal. BP, a decrease in TOC, LOI and TN is visible. C:N ratios increase from 8 at the bottom of the profile to 14 at 8,900 cal. BP. Values stay constantly around 14 until 800 cal. BP, then they increase slightly with a maximum of 16.7 at 200 cal. BP until values decrease to 12 after 150 cal. BP. The total sulphur (TS) profile is characterised by fluctuating values before 8,900 cal. BP, rapidly declining values until 6,750 cal. BP, slowly declining to constant values around 0.3 wt. % until 800 cal. BP, and rising values in the youngest sediments (*Fig. 4.9*). TS increases to values of 0.6 wt. % after 150 cal. BP, while the overall maximum of 1.5 wt. % can be seen at 9,050 cal. BP. C:S ratios increase from 0 at the bottom of the core to values between 75 and 80 at 4,100 cal. BP. They fluctuate around these values until they decrease to values around 40 in the sediments after 150 cal. BP.

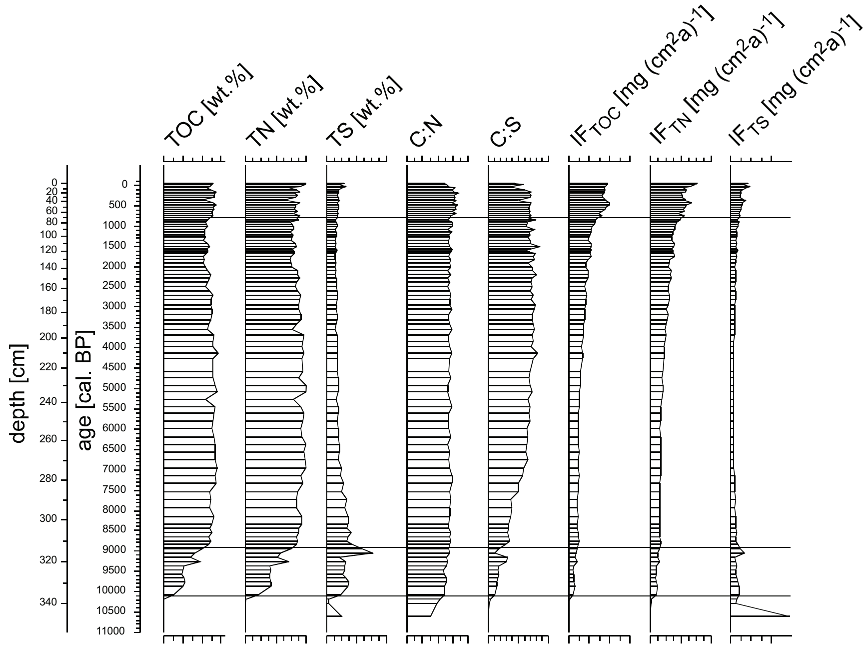


Figure 4.9: Total organic carbon (TOC), nitrogen (TN), and sulphur (TS), C:N and C:S ratios, and specific influx rates for TOC (IF_{TOC}), TN (IF_{TN}), and TS (IF_{TS}) for Reiarsdalsvatnet. Sediment zones are indicated by solid lines.

The influx rates of TOC (IF_{TOC}), TN (IF_{TN}) and TS (IF_{TS}) mainly reflect the sedimentation rates (*Fig. 4.9*). Very low IF_{TOC} values (<0.05 mg cm^{-2} a^{-1}) together with the maximum in IF_{TS} values (0.14 mg cm^{-2} a^{-1}) are found before 10,100 cal. BP. All influx values increase towards the top of the profile with faster increasing values after 800 cal. BP. Maximum IF_{TOC} (2.01 mg cm^{-2} a^{-1}) values are reached at 450 cal. BP and maximum IF_{TN} values occur at the sediment surface (0.15 mg cm^{-2} a^{-1}).

Isbenttjønn

LOI, TOC and TN show low contents before 9,300 cal. BP (*Fig. 4.6, 4.10*). From 9,300 cal. BP until 8,600 cal. BP they increase to reach values around 48 wt. % LOI, 25 wt. % TOC and 1.5 wt. % TN. Values remain at this level until 1,500 cal. BP, when they start to increase. The maxima of TOC and TN are reached at 600 cal. BP with 28.2 wt. % and 1.9 wt. %, respectively. As in Reiarsdalsvatnet, TN resembles TOC well (*Fig. 4.10*), thus the major part of nitrogen is bound organically. C:N ratios increase from the bottom of the core until 8,600 cal. BP, where they reach values between 15 and 17 (*Fig. 4.10*). Until 1,500 cal. BP, C:N ratios are very much constant in this range. Ratios decrease slightly to reach values below 15 after 1,300 cal. BP. Total sulphur (TS) increases rapidly from the bottom of the profile to reach its maximum of 2.8 wt. % at 8,750 cal. BP (*Fig. 4.10*). Since then, TS values decrease, first rapidly until 6,000 cal. BP, and then more slowly. C:S ratios increase steadily until 1,300 cal. BP and reach constant values (around 70) thereafter. Maximum biogenic silica (BSi) values of

30 wt. % occur at 9,000 cal. BP (*Fig. 4.10*). After 8,600 cal. BP BSi values fluctuate between c. 16 wt. % and 23 wt. % with the exception of the period from 6,000 cal. BP until 4,450 cal. BP, where BSi values are below 16 wt. %.

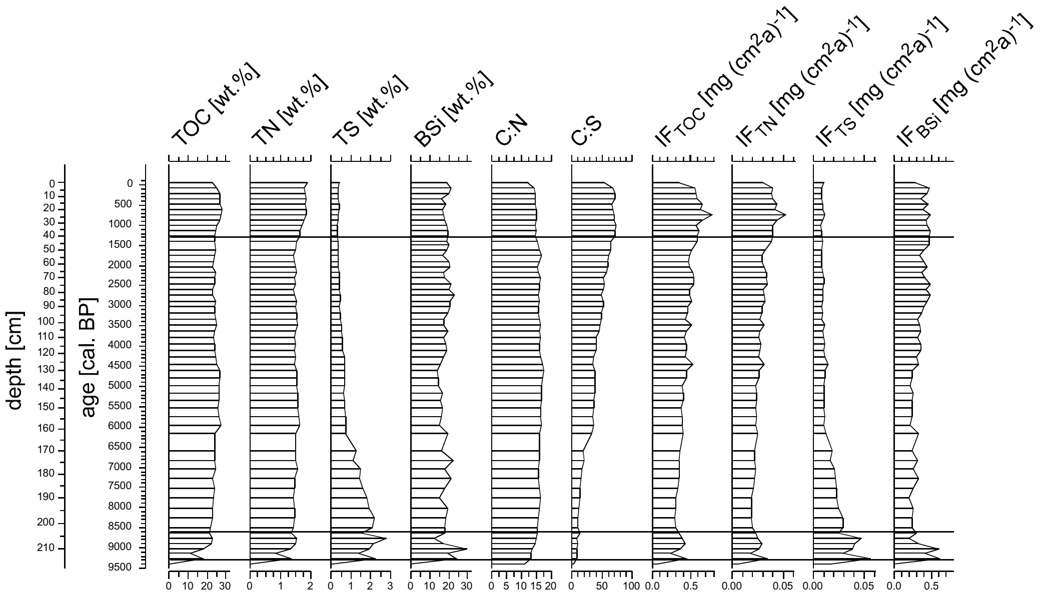


Figure 4.10: Total organic carbon (TOC), nitrogen (TN), and sulphur (TS), biogenic silica (BSi), C:N and C:S ratios, and specific influx rates for TOC (IF_{TOC}), TN (IF_{TN}), TS (IF_{TS}), and BSi (IF_{BSi}) for Isbenttjønn. Sediment zones are indicated by solid lines.

IF_{TOC} and IF_{TN} generally increase from the bottom to the top of the profile (*Fig. 4.10*). Local maxima are reached between 9,300 cal. BP and 8,600 cal. BP with absolute maxima of IF_{TOC} (0.78 mg cm^{-2} a^{-1}) and IF_{TN} (0.52 mg cm^{-2} a^{-1}) at 750 cal. BP. Further to the top influxes decrease slightly. IF_{TS} show their absolute maximum of 0.06 mg cm^{-2} a^{-1} at 9,250 cal. BP and high values until 8,600 cal. BP (*Fig. 4.10*). Above, influx rates decrease similarly to TS values, with a rapid decrease until 6,000 cal. BP and more slowly decreasing values towards the top. Regarding the influx rates of biogenic silica (IF_{BSi}), three distinct phases can be observed: High values up to 0.61 mg cm^{-2} a^{-1} between 9,300 cal. BP and 8,800 cal. BP, a phase of influxes below 0.31 mg cm^{-2} a^{-1} from 8,800 cal. BP cm to 4,450 cal. BP, and influxes above 0.31 mg cm^{-2} a^{-1} from 4,450 cal. BP to the top (*Fig. 4.10*).

Pollen analyses

In the following, results of pollen analysis and results of the examination of the coarse fraction of the pollen samples are presented. The zonations are based on the pollen results ('microscopic data') and are transferred to the graphs of the coarse fractions ('macroscopic data'). Ages of the zonations are rounded to the nearest 100 years.

Reiarsdalsvatnet

Seven statistically significant local pollen assemblage zones (RVpz 1 to RVpz 7) were found in Reiarsdalsvatnet (*Fig. 4.11, 4.12*).

RVpz 1: 10,500 – 10,200 cal. BP

RVpz 1 is characterised by maximum values of herb pollen (c. 50 %), mainly Poaceae and *Artemisia* (*Fig. 4.11*). *Salix*, *Betula* and *Pinus sylvestris* are the dominant tree pollen. No consistent differentiation was possible between pollen of tree birch (*B. pubescens*) and pollen of dwarf birch (*B. nana*). In the macroscopic data, the zone is characterised by high values of sand and low values of detritus (*Fig. 4.12*).

RVpz 2: 10,200 – 9,900 cal. BP

In RVpz 2, the amount of herb pollen decreases to c. 10 % (*Fig. 4.11*). *Betula* is dominant, reaching its Holocene maximum, as does *Juniperus communis*. *Salix* decreases and *Pinus sylvestris* shows comparable percentages as in RVpz 1. The rise of *Corylus avellana* begins at 9,950 cal. BP. *Dryopteris*-type spores reach a local maximum of 7 %. A peak of macroscopic charcoal can be observed in this zone, together with increasing detritus and decreasing sand values (*Fig. 4.12*).

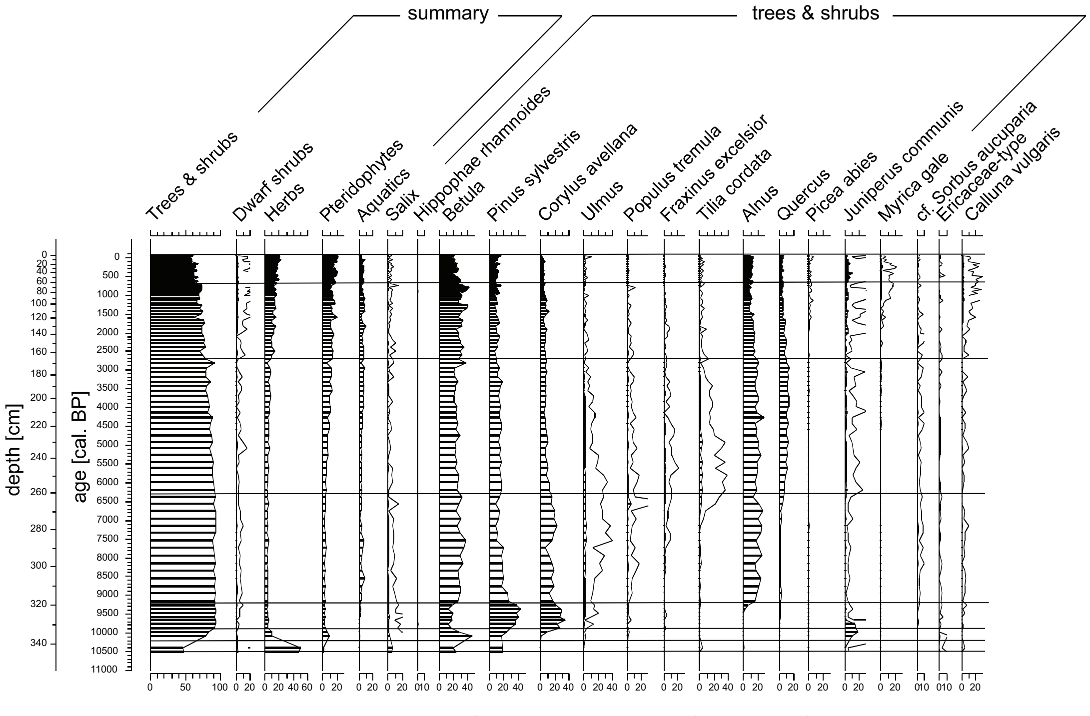


Figure 4.11: Simplified pollen percentage diagram of selected taxa and species turnover (DCA axis 1 sample scores [SD]) for Reiarsdalsvatnet, including local pollen assemblage zones (RVpz) and chronozones (cf. Lang 1994, Moen 1999). The hollow silhouettes denote a 10-fold exaggeration of the percentage values. SA: Subatlantic, SB: Subboreal, A: Atlantic, B: Boreal, PB: Preboreal.

RVpz 3: 9,900 – 9,200 cal. BP

Pinus sylvestris and *Corylus avellana* reach their Holocene maxima in RVpz 3, while *Betula* dips to its Holocene minimum and *Juniperus communis* decreases from values over 15 % at the beginning of the zone to values below 2 % after 9,700 cal. BP (*Fig. 4.11*). The first occurrences of *Ulmus, Populus tremula* and *Quercus* pollen are seen in this zone, as is the rise of *Alnus* pollen at 9,350 cal. BP. Microscopic *Pinus* stomata and macroscopic *Pinus* budscales are present (*Fig. 4.12*). Microscopic charcoal peaks, while macroscopic charcoal is absent. An increase in the frequency of small detritus can be observed in the macroscopic data.

RVpz 4: 9,200 – 6,300 cal. BP

This zone is characterised by the dominance of *Betula*, *Pinus sylvestris*, *Corylus avellana* and *Alnus* (*Fig. 4.11*). *Betula* and *Alnus* increase and *P. sylvestris* and *C. avellana* decrease, compared to the previous assemblage zone. *Ulmus* and *Populus tremula* pollen reach their Holocene maxima, *Fraxinus excelsior*, *Tilia cordata* and *Quercus* increase in the second half of this zone. In the aquatic flora, percentages of *Isoëtes* spores rise. Microscopic and macroscopic charcoal reach high values between 8,000 cal. BP and 6,500 cal. BP.

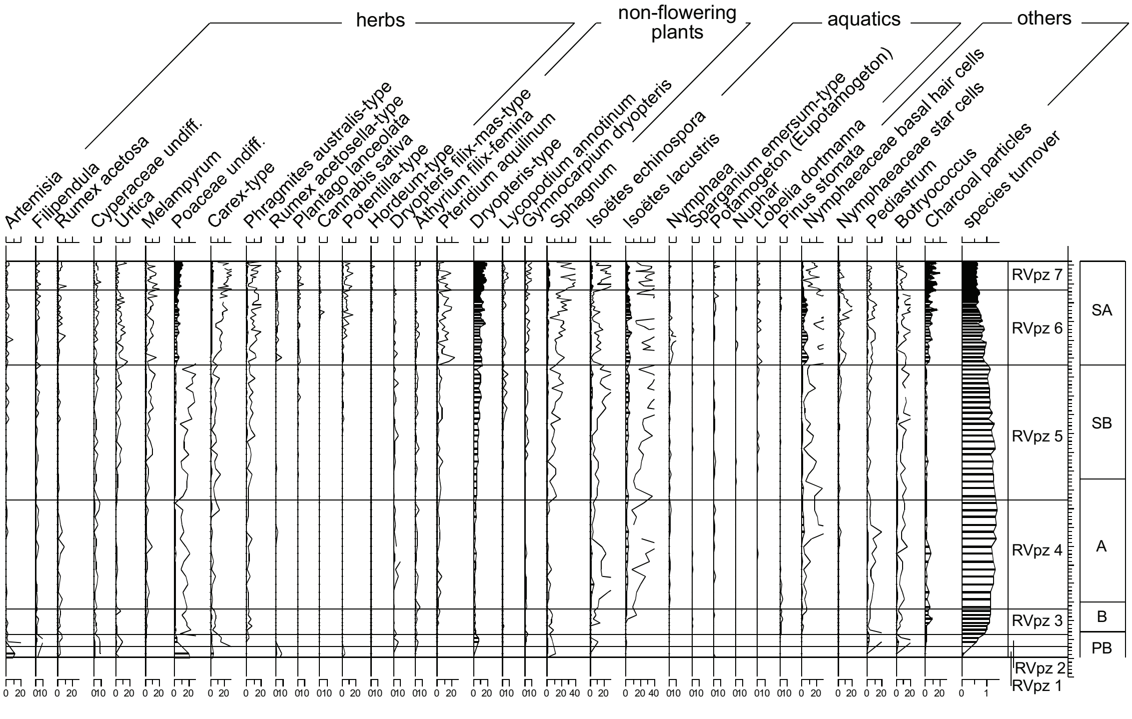


Figure 4.11: - continued -

High values of detritus and the presence of fern sporangia can be observed in the macroscopic data (*Fig. 4.12*). From 7,350 cal. BP on, high values of macroscopic Nymphaeaceae 'star cells' and *Daphnia* ephippia are characteristic.

RVpz 5: 6,300 – 2,700 cal. BP

In RVpz 5, the beginning of declining tree pollen, together with the slight increase in herb pollen and more distinct increase in fern spores can be seen (*Fig. 4.11*). The decrease in tree pollen is mainly due to the distinct decrease in *Corylus avellana* and a slight decrease in *Betula*. *Ulmus* also decreases, while *Fraxinus excelsior*, *Tilia cordata* and *Quercus* reach their Holocene maxima and *Juniperus communis* rises slightly. Poaceae show a rising trend but their percentages remain below 3 %. *Dryopteris*-type and *Sphagnum* rise distinctly and *Isoëtes* characterise the aquatic taxa. Macroscopic Nymphaeaceae 'star cells' and *Daphnia* ephippia decrease, and macroscopic charcoal values are low (*Fig. 4.12*).

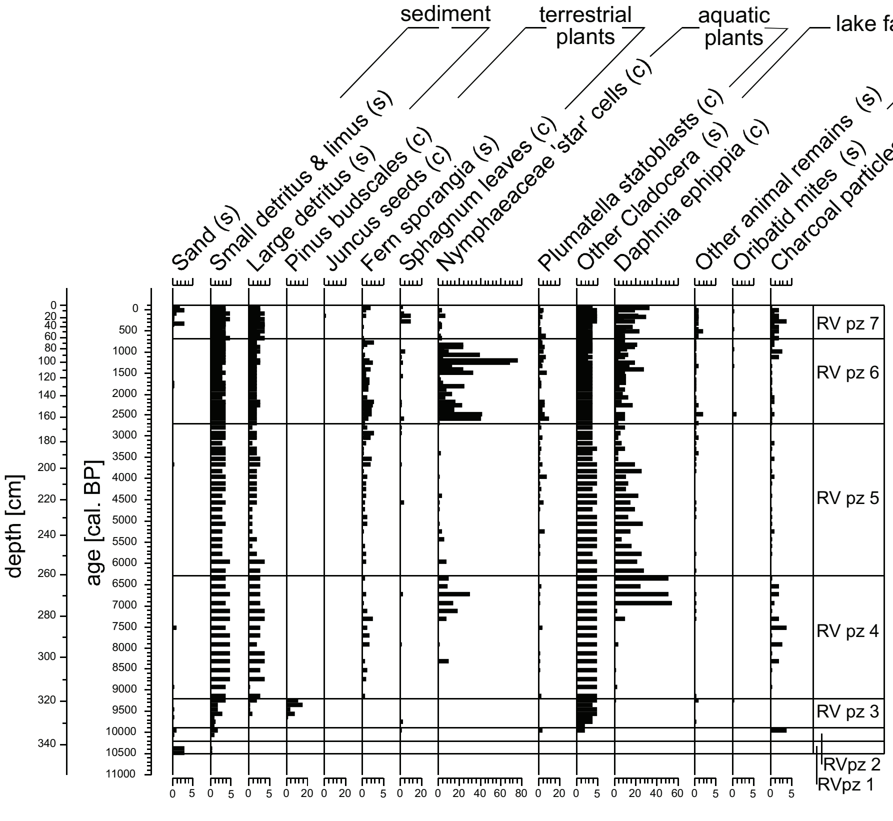


Figure 4.12: Results from the examination of the coarse fraction of the Reiarsdalsvatnet pollen samples. 'c' indicates count data, 's' indicates that values are given on a 5 point scale from 'absent' (= 0) to 'abundant' (= 5).

RVpz 6: 2,700 – 700 cal. BP

The trend of decreasing tree pollen is continued in RVpz 6 (*Fig. 4.11*). In comparison to RVpz 5, herb percentages rise distinctly to values around 15 %, while fern spores rise more slowly. *Betula* and *Juniperus communis* values are higher than in RVpz 5. *Pinus sylvestris* and *Corylus avellana* show comparable values to RVpz 5, while *Alnus* and *Quercus* decrease and *Ulmus*, *Fraxinus excelsior* and *Tilia cordata* pollen are present in very low numbers. *Picea abies* pollen occurs from 1,900 cal. BP in very low numbers and at the same time, and C*alluna vulgaris* and *Myrica gale* start to rise. Poaceae and *Carex*-type increase in this pollen assemblage zone, as do *Phragmites australis*-type, *Potentilla*-type, *Dryopteris*-type and *Sphagnum*. *Pteridium aquilinum* spores and microscopic charcoal rise abruptly with the onset of RVpz 6. The aquatic flora is characterised by *Isoëtes lacustris* and maximum values of microscopic Nymphaeaceae 'basal hair cells' and 'star cells', as well as high values of macroscopic Nymphaeaceae 'star cells' (*Fig. 4.12*).

RVpz 7: 700 cal. BP to present

The further decrease in tree pollen in the youngest zone to values below 60 % is mainly due to the decrease in *Betula* (*Fig. 4.11*). *Juniperus communis*, *Calluna vulgaris* and *Myrica gale* reach (local) maxima, as do Poaceae*,* *Carex*-type, *Dryopteris*-type and *Sphagnum*. Microscopic and macroscopic charcoal values are high and *Juncus* seeds are present. Nymphaeaceae decline drastically in the microscopic and the macroscopic data, while *Isoëtes echinospora* reaches maximum values. In the youngest part of this zone, higher values of sand and *Sphagnum* leaves can be seen.

Isbenttjønn

For the Isbenttjønn pollen profile, four local pollen assemblage zones (ITpz 1 to ITpz 4) can be distinguished (*Fig. 4.13*). These pollen zones are transferred to the profile of the data from the coarse fraction (*Fig. 4.14*).

ITpz 1: 9,400 – 8,100 cal. BP

ITpz 1 is characterised by up to 90 % tree pollen with the dominant pollen taxa being *Betula* and *Pinus sylvestris* (*Fig. 4.13*). *Juniperus communis* occurs at values between 5 % and 10 %. *Salix* and *Corylus avellana* show the highest values in the oldest sediment samples and decreasing values in the younger parts of the pollen zone. *Ulmus* and *Quercus* pollen are present and *Alnus* pollen begins to rise at 9,100 cal. BP. The herbaceous taxa are dominated by Poaceae, while fern spores are of minor importance.

ITpz 2: 8,100 – 3,300 cal. BP

Only few changes occur in ITpz 2 (*Fig. 4.13*). Tree pollen accounts for 80 percent of the pollen sum. *Betula*, *Pinus sylvestris*, *Alnus* and *Juniperus communis* are the most important taxa, while *Corylus avellana* decreases. *Ulmus* and *Quercus* reach their Holocene maximum values, but the percentages remain below 5 %. Poaceae, Cyperaceae undiff., and *Carex*-type are the dominant herb taxa, with the latter increasing in the younger part of ITpz 2. *Dryopteris*-type spores and *Sphagnum* increase.

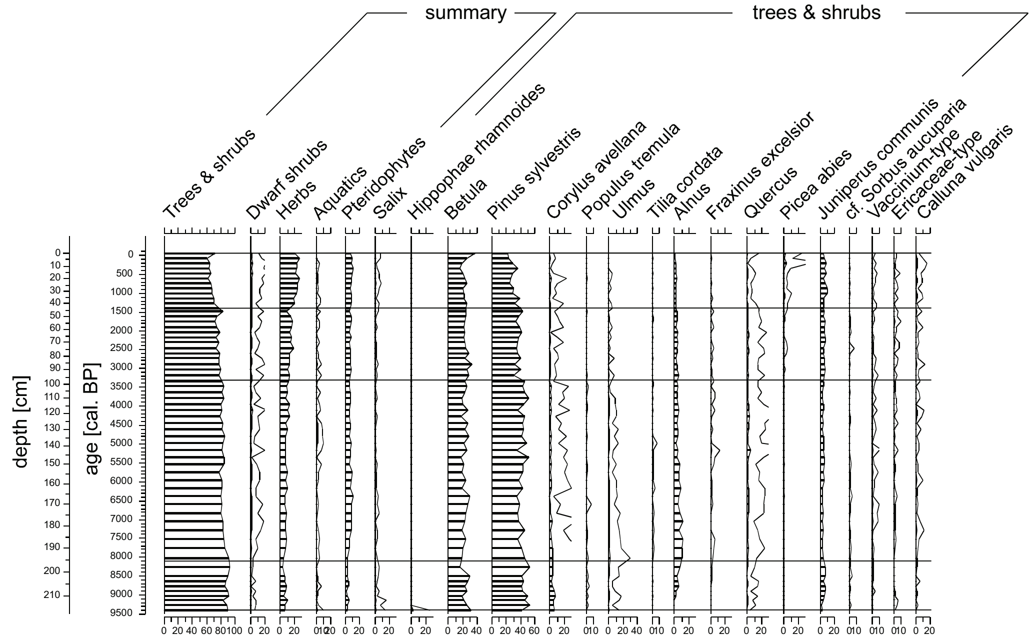


Figure 4.13:Simplified pollen percentage diagram of selected taxa and species turnover (DCA axis 1 sample scores [SD]) for Isbenttjønn, including local pollen assemblage zones and chronozones (cf. Lang 1994, Moen 1999). The hollow silhouettes denote a 10-fold exaggeration of the percentage values. SA: Subatlantic, SB: Subboreal, A: Atlantic, B: Boreal.

ITpz 3: 3,300 – 1,400 cal. BP

Tree pollen is decreasing slightly in ITpz 3 and herb pollen becomes more important (*Fig. 4.13*). *Betula* values do not change, *Pinus sylvestris* decreases, and *Juniperus communis* increases slightly. A continuous curve of *Picea abies* pollen begins at 1,750 cal. BP. Poaceae and *Carex*-type increase slightly. *Dryopteris filix-mas*-type decreases, while *Dryopteris*-type remains unchanged and *Selaginella selaginoides*, *Sphagnum* and microscopic charcoal increase, as well as *Daphnia* ephippia (*Fig. 4.14*).

ITpz 4: 1,400 cal. BP to present

Betula remains dominant, *Pinus sylvestris* decreases and reaches its minimum (<25 %) in the youngest sediments (*Fig. 4.13*). *Quercus* pollen decreases also, while *Picea abies* and *Juniperus communis* show their highest values in this assemblage zone. Higher values than in the older pollen zones are distinct in *Calluna vulgaris*, Poaceae, Cyperaceae undiff., and *Carex*-type. *Selaginella selaginoides*, *Sphagnum* and microscopic charcoal reach their Holocene maxima and *Daphnia* ephippia are abundant in this zone as well (*Fig. 4.14*).

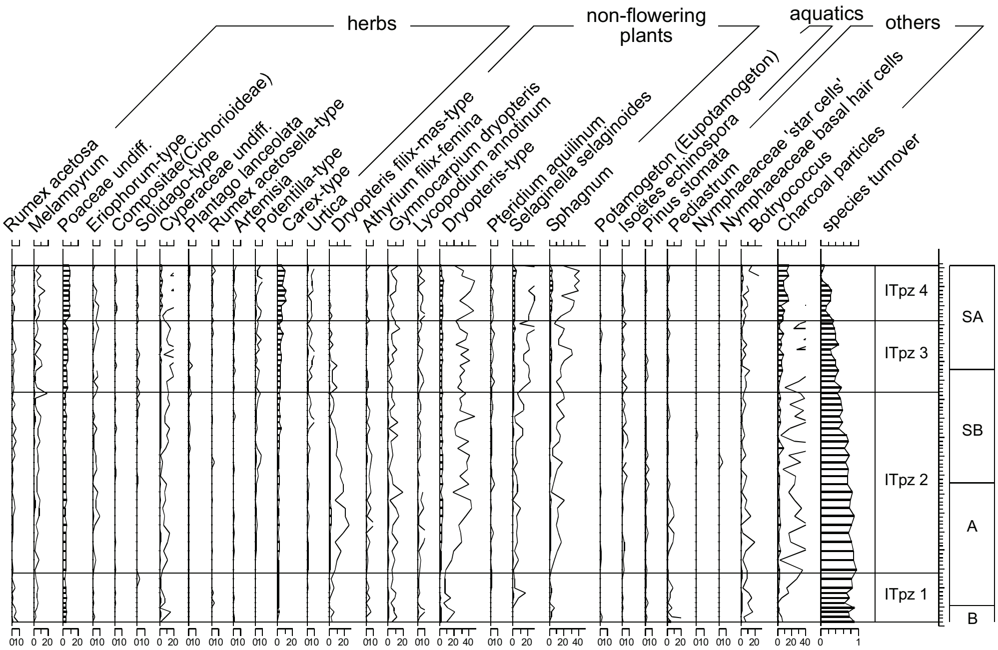


Figure 4.13: - continued –

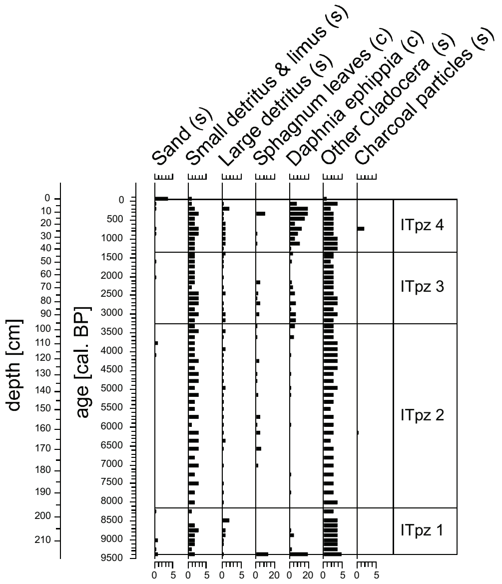


Figure 4.14: Results from the examination of the coarse fraction of the Isbenttjønn pollen samples. 'c' indicates count data, 's' indicates that values are given on a 5 point scale from 'absent' (= 0) to 'abundant' (= 5).

Species turnover

The DCA sample scores on axis 1, indicating the amount of compositional change between samples, are plotted stratigraphically in the pollen analysis plots (*Fig. 4.11, 4.13*). In Reiarsdalsvatnet, the gradient is short, with the largest changes occurring in RVpz 1, RVpz 2 and RVpz 6. Values in RVpz 3, RVpz 4 and RVpz 5 show constant conditions with high values and RVpz 7 constant conditions with relatively low values. In Isbenttjønn, the gradient is shorter than in Reiarsdalsvatnet. Values show a general decreasing trend over the Holocene, with the highest values in ITpz 1 and ITpz 2 and the lowest values in the youngest sediment (ITpz 4).

Interpretation and discussion

Lake genesis, sedimentation history, and trophic state

To reconstruct the lakes' ontogeny, sediment proxies are discussed together with the information about the aquatic and shore flora, as well as faunal remains, derived from pollen analysis. The discussed proxies and taxa are compiled in *Figure 4.15* (Reiarsdalsvatnet) and *Figure 4.16* (Isbenttjønn). The zonations are the main zones from the sediment proxy data.

Reiarsdalsvatnet

Lake genesis and initial phase (before 10,100 cal. BP)

As Reiarsdalsvatnet is located in the area of the Ra (i.e., Younger Dryas) terminal moraine, the evolution of the early lake basin is directly connected to glacial influence. No information about the genesis of the lake is known, but its location in an oblong channel structure including another lake situated south-west of Reiarsdalsvatnet and the brook running in a western direction (*Fig. 2.5*), indicates that the land surface was shaped by subglacial melt water erosion. The location of the glacio-fluvial deposits west of Reiarsdalsvatnet (*Fig. 2.8*) suggests that the lake developed because of damming of running water by this material. Bands of clay in the lower clastic part of the profile Reiarsdalsvatnet indicate the existence of a body of standing water before the onset of organic sedimentation at 10,100 cal. BP. No closer age estimation can be given for this clastic part of the profile, because the age-depth model for Reiarsdalsvatnet is only applicable for the organic sediment. However, the onset of sedimentation of organic matter in Reiarsdalsvatnet is distinctly later than the start of the final ice retreat after the Younger Dryas at 11,500 cal. BP (Bondevik and Mangerud 2002). This can be explained by local differences of the ice retreat, as Anundsen (1985) found that the ice front in Setesdal was most likely located at the Ra-moraines from the Younger Dryas to the Preboreal/Boreal transition (9,000 ^{14}C BP/c. 10,100 cal. BP). This is supported by the onset of organic sediment formation in Reiarsdalsvatnet at 10,100 cal. BP.

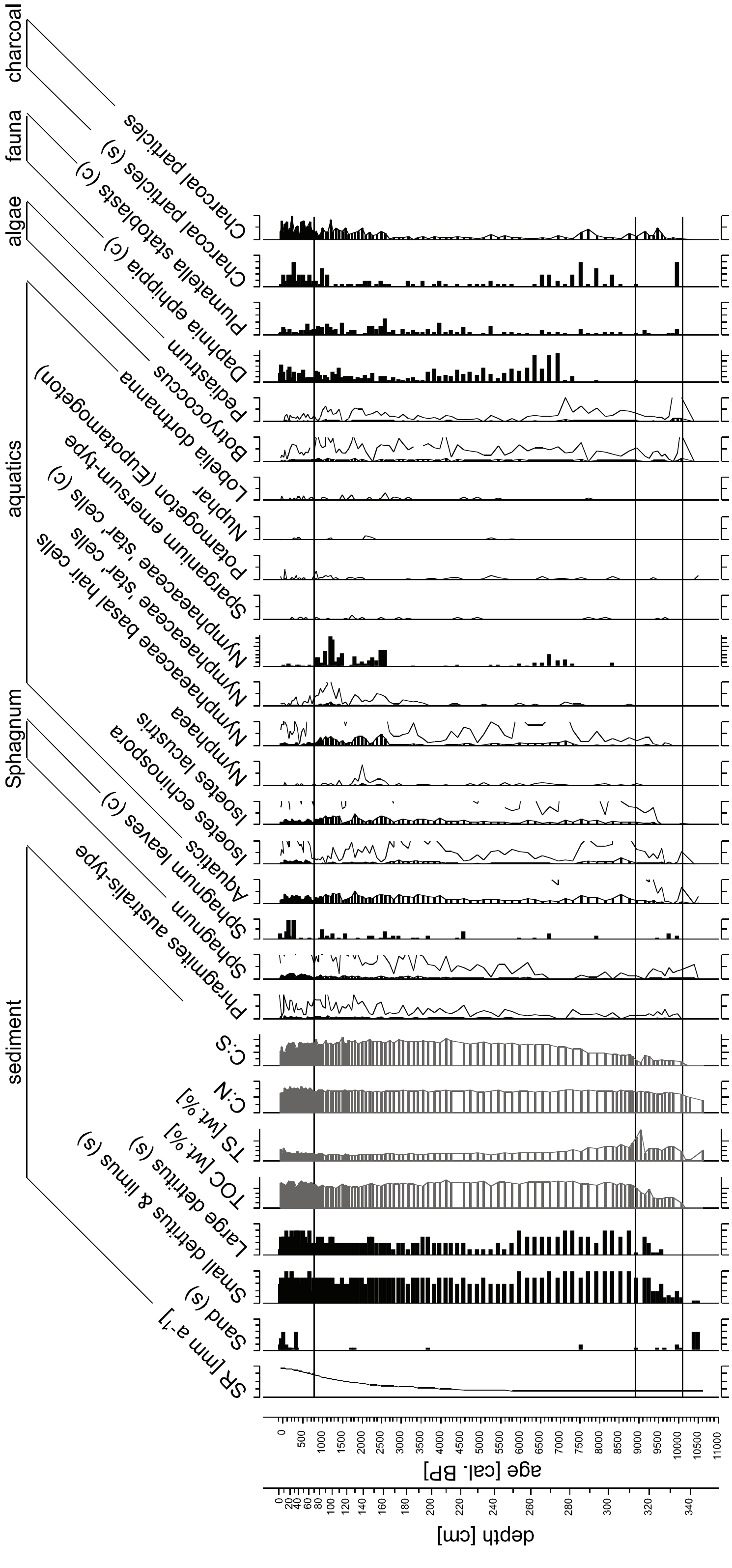


Figure 4.15: Sediment proxies, indicators for aquatic and shore flora, and faunal remains from Reiarsdalsvatnet. Line graph: sedimentation rates (SR); grey silhouettes: percentage data of total organic carbon (TOC), total sulphur (TS), and C:N and C:S ratios; black silhouettes: pollen percentage data, some with a 10-fold exaggeration; bar graphs: coarse fraction of pollen samples where 'c' indicates count data and 's' indicates values given on a 5 point scale.

Phase of stabilising catchment conditions (10,100 cal. BP to 8,900 cal. P)

Since the beginning of the organic sediment formation, the organic material mainly originated from autochthonous production, as documented by C:N ratios below 10 (Meyers and Teranes 2001), (*Fig. 4.15*). The presence of *Isoëtes*, *Pediastrum* and *Botryococcus* from 10,100 cal. BP, of Cladocera a century later, and the rise of aquatic macrophytes substantiate the onset of autochthonous production (*Fig. 4.15*). Since significant autochthonous production is only possible if certain levels of temperature, light and nutrients are available these requirements must have been reached by that time. The autochthonous production together with the rapid decline in clastic material in the sediment, as indicated by the declining dry density values (*Fig. 4.3*), shows that inwash of eroded material quickly diminished. Thus sediment and young soils in the catchment must have stabilised rapidly after ice retreat. Around 9,600 cal. BP, records of clastic material in the lake sediment (*Fig. 4.1*) stop at the same time as *Juniperus* pollen decreases (*Fig. 4.11*), indicating increasing vegetation density. The following increase in TOC and LOI percentages between 9,400 cal. BP and 8,900 cal. BP is due to an absolute increase of organic matter in the lake sediment, as seen in the IF_{TOC} values (*Fig. 4.9*). This evidences increased autochthonous productivity and allochthonous input of terrestrial organic material. The latter is indicated by the detritus in the coarse pollen fraction and increasing C:N ratios (Meyers and Teranes 2001), (*Fig. 4.15*). In addition, C:N ratios larger than 10 to 15 indicate dystrophic conditions in a lake (Håkanson and Jansson 1983, Hansen 1959). Since C:N ratios in Reiarsdalsvatnet do not exceed 14 during this phase and since macrophyte presence and clear-water conditions are indicated by the continuous curve of *Isoëtes lacustris* and *Isoëtes echinospora* spores from c. 9,500 cal. BP, Reiarsdalsvatnet is categorised as mesohumic.

The peak in total sulphur at 9,050 cal. BP is not mirrored in any of the analysed parameters and cannot be interpreted from the available data. It might be due to internal lake processes in connection with the onset of stable conditions in the lake or it may be an artefact of early diagenesis.

Phase of stable catchment conditions (8,900 cal. BP to 800 cal. BP)

After 8,900 cal. BP the percentage values of organic matter proxies stay almost constant until 800 cal. BP, indicating no changes in the sediment composition (*Fig. 4.15*). Almost no sand was found in the coarse fraction of the pollen samples. Erosion in the catchment thus played a very minor role and soils in the catchment were stable.

With regard to the absolute influxes (*Fig. 4.9*) increasing IF values show that larger amounts of organic matter have been preserved in the sediment. This together with C:N ratios between 13 and 15 (*Fig. 4.9*) indicates that the influx of both, allochthonous and autochthonous organic matter increased. The latter points to an increasing productivity in the lake. Still, oligotrophic conditions prevailed as indicated by the presence of *Isoëtes lacustris* (*Fig. 4.15*). Though a mesohumic status of Reiarsdalsvatnet is indicated by the C:N ratios between 13 and 15 (Håkanson and Jansson 1983, Hansen 1959), the lake water was clear enough to allow for the growing of Isoëtides and Phragmites (*Fig. 4.15*).

C:S ratios increase steadily, especially during the first half of this phase. Several studies show that sulphur in profundal sediments of unpolluted lakes is predominantly bound organically (King and Klug 1982, Nriagu and Soon 1985, Urban *et al.* 2001). Pyrite formation by bacterial reduction of organic sulphur is unlikely to be observed in oligotrophic lakes (Nriagu and Soon 1985). Thus the C:S ratios in Reiarsdalsvatnet are most likely a feature of the organic matter in the sediment. In unpolluted lakes, typical C:S ratios between 25 and 60 can be observed in profundal sediments, while littoral sediments tend to have C:S ratios higher than 60 (Nriagu and Soon 1985, Olsson *et al.* 1997). This is due to higher percentages of macrophytes and plant debris in the littoral sediments, since C:S ratios for soil organic matter typically vary between 60 and 120, while those for seston vary between 16 and 30 (Nriagu and Soon 1985). Only in eutrophic lakes C:S ratios distinctly below 20 are found, due to external sulphur input and/or oxygen depletion in the hypolimnion (Gorham *et al.* 1974, Nriagu and Soon 1985). The steadily increasing C:S ratios in Reiarsdalsvatnet are thus possibly a sign of increasing terrestrialisation of the lake, leading to an expansion of the littoral area. An increase in macrophytes and *Plumatella* statoblasts (*Plumatella* lives in the littoral zone and is often found on aquatic plants) are also observed (*Fig. 4.15*). Notably, the strongest increase in C:S ratios around 7,000 cal. BP coincides with high numbers of macroscopic Nymphaeaceae ‘star cells’ (*Fig. 4.15*), which supports the interpretation that increased proportions of lake organic matter originating from macrophytes are the cause of increasing C:S ratios.

In the youngest part of this stable period (from 2,600 cal. BP until 800 cal. BP), the increase in sedimentation rates and influx, triggered by an increased influx of organic matter, is the strongest in the whole profile. Since no changes in the C:N and C:S ratios are observed during this sub-phase, the source of organic matter does not change but the amount of sediment accumulation and preservation increases. This suggests higher productivity in the lake, but the presence of aquatic macrophytes (*Isoëtes*, Nymphaeaceae, *Lobelia*; *Fig. 4.15*) still indicates oligotrophic, clear-water conditions. The presence of the macrophytes possibly documents a further expansion of the littoral area.

Phase of increasing human impact (800 cal. BP to present)

Constant values of aquatics indicate macrophyte presence in Reiarsdalsvatnet during the last 800 years, but the decrease in *Nymphaea* is striking (*Fig. 4.15*). The increase in C:N ratios to values above 16 during the first centuries of this phase indicates a higher input of terrestrial organic matter. In addition, it is a sign for increased humic status (Håkanson and Jansson 1983) with the staining of the water also being documented by the decrease in Isoëtides (*Fig. 4.15*). During the last 150 years, high TS values together with decreasing C:N and C:S ratios (*Fig. 4.15*) are a sign of human impact since industrialisation. Higher nutrient availability caused an increase in autochthonous production documented in decreasing sediment C:N ratios (*Fig. 4.15*). High TS values are suspected to be due to increased external input rather than to limitation of oxygen, since none of the other parameters indicate hypolimnetic anoxia.

Isbentjønn

Lake genesis and initial phase (before 9,300 cal. BP)

Isbenttjønn is located in a glacially shaped landscape within an area partly covered by till (*Fig. 2.11*). No specific information is known about the genesis of the Isbenttjønn basin. Deglaciation of the region occurred after c. 9,000 ^{14}C BP (c. 10,100 cal. BP), but the exact age of deglaciation is uncertain. While Indrelid (1994) states that the process of deglaciation on the mountain plateau of Hardangervidda, north of Isbenttjønn, was completed by c. 9,000 ^{14}C BP (c. 10,100 cal. BP), Andersen (1980) indicates that the upper part of Setesdal was still covered with ice at 9,000 ^{14}C BP. Blystad and Selsing (1988) in their study in the mountain area west of Setesdal note that the final deglaciation of this mountain area occurred simultaneously with Setesdal at c. 8,800^{14}C BP (c. 9,800 cal. BP). However, Isbenttjønn as a body of still water started to exist only shortly before 9,300 cal. BP. This is documented by the fact that only the uppermost centimetre of the clastic part of the profile is sandy clay, while coarser fractions of gravel and sand are present below (*Fig. 4.1*). Above this sandy clay, the onset of sedimentation of organic material is found at 9,300 cal. BP. The origin of the lake may thus either be connected to a kettle-hole structure or to a possible shift in the river course of River Ralfdøla after the local deglaciation, causing a damming by running water sediments (*Fig. 2.9*).

Phase of stabilising catchment conditions (9,300 cal. BP to 8,600 cal. BP)

From 9,300 cal. BP to 8,600 cal. BP, sedimentation and preservation of organic matter increased, as seen from the TOC percentages (*Fig. 4.16*). Increasing C:N ratios

(13 to 15.4) indicate that an increasing amount of organic matter in the sediment is of terrestrial origin and are a sign for meso- to polyhumic conditions in the lake.

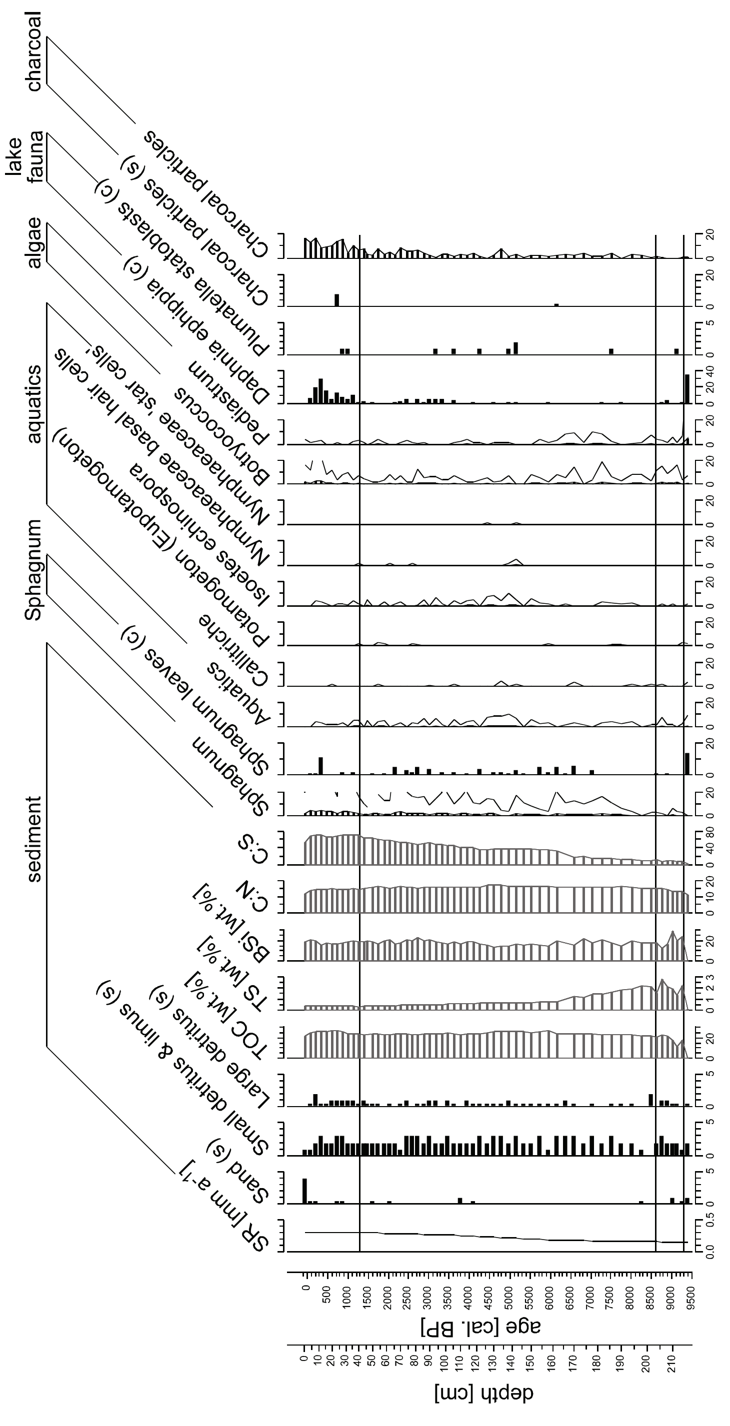


Figure 4.16: Sediment proxies, indicators for aquatic and shore flora, and faunal remains from Isbenttjønn. Line graph: sedimentation rates (SR); grey silhouettes: percentage data of total organic carbon (TOC), total sulphur (TS), biogenic silica (BSi), and C:N and C:S ratios; black silhouettes: pollen percentage data, some with a 10-fold exaggeration; bar graphs: coarse fraction of pollen samples where 'c' indicates count data and 's' indicates values given on a 5 point scale.

From the lithology (*Fig. 4.1*) and the findings of sand in the coarse fraction of the pollen samples (*Fig. 4.14*), it is likely that erosion in the catchment occurred, but the soils became more and more stable. In this context, erosion may also have caused a relatively high input of external sulphur, documented by the high TS values (*Fig. 4.16*). This external input would explain the C:S ratios below 10 (Gorham *et al.* 1974, Nriagu and Soon 1985), (*Fig. 4.16*), but oxygen depletion in the sediment or at the sediment-water interface may also have contributed to the low C:S ratios. The sulphur most likely is incorporated into the sediment as iron sulphide, shown by described darkening of the sediment on exposure to air (*Fig. 4.1*). In addition, the availability of iron is seen by the presence of the iron-phosphate vivianite in the sediment (*Fig. 4.1*).

Diatoms contribute most to the autochthonous production, as indicated by maxima in biogenic silica (*Fig. 4.16*). These high BSi percentages are most likely due to the availability of nutrients like phosphorus, silica and sulphur from catchment erosion. Macrophytes play a minor role during this phase (*Fig. 4.16*).

Phase of stable catchment conditions (8,600 cal. BP to 1,300 cal. BP)

From 8,600 cal. BP on, clastic inwash is of minor importance in Isbenttjønn, as documented in the lithology (*Fig. 4.1*) and the low numbers of findings in the coarse fraction of the pollen samples (*Fig. 4.14*). This indicates soil stability in the catchment.

During this period, a nearly constant sedimentation of organic matter is shown by the TOC and IF_{TOC} values (*Fig. 4.16*). C:N ratios are constant as well (*Fig. 4.16*), and ratios over 15 indicate that a part of the organic influx derives from terrestrial sources. This, together with low numbers of large detritus found in the coarse fraction of the pollen analysis material (*Fig. 4.16*) shows that the allochthonous influx mainly consists of decomposed organic matter, and indicates further dystrophication. The autochthonous productivity is mainly based on algae production as documented by high values of biogenic silica and the presence of *Botryococcus* and *Pediastrum* (*Fig. 4.16*). Only low numbers of macrophyte remains are found. The continuous presence of *Isoëtes echinospora* (*Fig. 4.16*) indicates that the lake was oligotrophic and not a fully developed brown-water lake, though further dystrophication occurred.

The C:S ratios are in a range typically found in profundal sediments of oligotrophic lakes (Nriagu and Soon 1985), (*Fig. 4.16*). They generally increase with decreasing depth, indicating slowly advancing terrestrialisation of the lake, as explained above. In addition, C:S ratios below 40 together with evidence of iron staining of the sediment found in the lithology (*Fig. 4.1*) suggest some oxygen depletion at the sediment-water interface before 4,300 cal. BP. Whether this oxygen depletion is due to a stable stratification during winter, because of long lasting ice-cover, or during summer, caused by higher lake level or less wind energy, cannot be decided from the available data.

Youngest phase (1,300 cal. BP to present)

An increase of lacustrine production in comparison to allochthonous organic matter is indicated by C:N ratios below 15 in the period from 1,300 cal. BP to present. This points to an increased productivity and a lower humic status. Since values of biogenic silica are constant on a high level, this increase in autochthonous productivity is not related to increasing diatom production but on other algae, indicated e.g., by the increase in *Botryococcus* (*Fig. 4.16*). Increasing numbers of *Daphnia* ephippia in the sediment can be related to larger *Daphnia* populations (Jeppesen *et al.* 2003). No changes in the macrophytes presence can be observed.

Local vegetation development

Pollen percentages do not represent proportions of plant species in the landscape directly. For the reconstruction of the catchment vegetation from pollen data certain limitations have to be taken into account. Most important are taxonomic limitations and differences between taxa in pollen production, pollen dispersal, and pollen preservation (Bennett and Willis 2001, Birks and Birks 1980). Difficulties like taxonomic limitations and the question of the representation of plants can be addressed by the analysis of macrofossils (e.g. Birks and Birks 2003, Gobet *et al.* 2005). At Reiarsdalsvatnet and Isbenttjønn, no macrofossil analysis was carried out, but qualitative information about macrofossil presence is available from the analysis of the coarse fraction of the pollen samples. In addition, the study of Eide *et al.* (2006) about the Holocene forest development in the Setesdal valley is considered, since this study includes pollen and macrofossil analyses. Especially, two lakes of the study are interesting in this context: Grostjørna (180 m asl) is located only c. 25 km north of Reiarsdalsvatnet and Lille Kjelavatn (1,000 m asl) only c. 15 km west of Isbenttjønn. The pollen- and macrofossil analyses of the sediments of these lakes should reflect similar regional vegetation patterns as Reiarsdalsvatnet and Isbenttjønn.

Reiarsdalsvatnet

The data from Reiarsdalsvatnet show that the arrival of *Betula* and *Pinus* took place before the onset of the formation of organic sediment at 10,100 cal. BP (*Fig. 4.11*). This is in line with Eide *et al.* (2006), who found that *Betula* spread in the Setesdal region before 10,500 cal. BP and that *Pinus* arrived in southern Setesdal about 400 years after *Betula*. The local presence of *Pinus* at 9,850 cal. BP is indicated by the first *Pinus* stomata and macroscopic *Pinus* budscales (*Fig. 4.12*).

High percentages of herbaceous pollen (mainly *Artemisia* and Poaceae) and fern spores (mainly Dryopteris-type) before 9,900 cal. BP (RVpz1 and 2; *Fig. 4.11*), together with the presence of *Salix*, *Betula*, *Pinus* and the increase in *Corylus* and *Juniperus* suggest that the vegetation was open *Betula* woodland with ferns and grasses. From 9,900 cal. BP until 9,200 cal. BP (RVpz 3), high tree pollen percentages indicate forest around the lake dominated by *Pinus* (presence of *Pinus* budscales), *Corylus*, and, to a lesser extent, *Betula*. The decline in *Juniperus* at 9,650 cal. BP might indicate closed forest cover thereafter. Pollen of warmth-demanding deciduous trees like *Ulmus*, *Populus*, *Tilia,* and *Quercus* show maximum Holocene abundances from 9,200 cal. BP to 2,700 cal. BP (RVpz 4 and 5). The presence of *Populus, Ulmus*, *Tilia* and *Quercus* macrofossils in Grostjørna (Eide *et al.* 2006) suggests that these deciduous trees were most likely locally present in the catchment of Reiarsdalsvatnet as well. This indicates the importance of deciduous trees in the mixed deciduous-coniferous forest. *Alnus* was common in wet areas (*Fig. 4.11*) and herbaceous plants were of minor importance.

High values in microscopic charcoal from c. 9,500 cal. BP to 7,400 cal. BP (*Fig. 4.11*), and in macroscopic charcoal from c. 8,000 cal. BP until c. 6,500 cal. BP (*Fig. 4.12*) suggests either a dry climate with high numbers of thunderstorm-caused fires, or early Mesolithic impact by local burning and/or settlements close to the lake. Charcoal peaks during this period are also found in Grostjørna (Eide *et al.* 2006). Mesolithic settlements in the mountains west and east of Setesdal have been recorded (e.g. Bang-Andersen 1986, Larsen 1981). They were most likely used seasonally for reindeer hunting by people living close to the coast. In the intermediate zone (the forested areas between the coast and the high mountains) Mesolithic transitory sites should have been present, but only a few sites have been found, which is most likely due to the lack of systematic research in this area (Bang-Andersen 1996). Setesdal has been suggested to be an access area for the higher mountains as well as an area of high resource availability like elk meat and hides during the main part of the Mesolithic (Bang-Andersen 1996). During the second half of this period, after 6,300 cal. BP, the decrease in tree pollen together with maxima in *Quercus* and *Juniperus*, increasing *Dryopteris*-type, Poaceae and *Carex*-type (*Fig. 4.11*) indicates an opening of the forest. Rising *Sphagnum* spore values point to the spread of wet areas/mires in the surrounding and might indicate the beginning of terrestrialisation.

The period from 2,700 cal. BP to 700 cal. BP (RVpz 6) is characterised by a further opening of the landscape, indicated by decreasing tree pollen, steadily increasing fern spores, and abruptly increasing herb pollen (*Fig. 4.11*). Deciduous trees like *Ulmus*, *Populus* and *Tilia* become less common in the forest. The increase or first appearance, respectively, of *Calluna vulgaris*, *Myrica gale*, Poaceae, *Carex*-type, *Rumex acetosella*, *Plantago lanceolata*, *Potentilla*-type, *Pteridium aquilinum*, *Hordeum*-type, *Dryopteris*-type and microscopic charcoal suggest the beginning of human activity including local burning and maybe the presence of human settlements in the area. Supposedly, with the onset of the Iron Age, human activity in the vicinity of the lake may have triggered enhanced nutrient input into Reiarsdalsvatnet. At Grostjørna, similar indicators of human activity are found after 2,800 cal. BP (Eide *et al.* 2006).

From 700 cal. BP to present (RVpz 7), today's mixed coniferous-deciduous forest established with *Betula*, *Pinus*, *Corylus*, *Alnus*, *Quercus* and *Juniperus* being the most important taxa (*Fig. 4.11*). The decrease in tree pollen and the increase in herbeacous pollen and fern spores progressed. A further opening of the landscape is evident, with dry areas indicated by Poaceae and *Dryopteris*-type, and wet areas by *Carex*-type and the presence of *Juncus* seeds (*Fig. 4.12*). However, constant values of *Juniperus* and *Calluna vulgaris*, preferring dry, open areas, and *Myrica gale*, growing on wet, open areas, suggest that the open areas would have persisted. Indicators for human activity, including *Rumex acetosella*, *Plantago lanceolata*, and *Hordeum*-type remain constant, but microscopic and macroscopic charcoal increase distinctly, indicating increasing human activity in the area. The abundance of *Sphagnum* suggests the increasing importance of mires in the catchment, probably due to mire development in the south-west of the lake (*Fig. 2.5*).

Isbentjønn

Pinus and *Betula* had already arrived in the region, when the formation of organic sediments in Isbenttjønn began at 9,300 cal. BP. This is confirmed by Eide *et al.* (2006), who found *Betula* and *Pinus* macrofossils in Lille Kjelavatn (1,000 m asl, c. 15 km west of Isbenttjønn) with the onset of lake sedimentation at 9,000 cal. BP. At Isbenttjønn, the pollen suggests the presence of *Betula-Pinus* woodland with *Salix* and *Juniperus* from the onset of the profile until 8,100 cal. BP (ITpz 1, *Fig. 4.13*). Pollen of deciduous trees like *Corylus*, *Populus*, *Ulmus*, *Tilia*, *Alnus* and *Quercus* most likely come from lower regions via long-distance transport. Poaceae and *Cyperaceae* undiff. dominate the herbaceous species.

From 8,100 cal. BP until 3,300 cal. BP (ITpz 2), tree pollen percentages are constant, but are slightly lower than before (*Fig. 4.13*). Tree pollen is dominated by *Betula* and *Pinus*, which indicate *Betula-Pinus* woodland, with *Juniperus* and greater amounts of Ericaceae being present. Eide *et al.* (2006) did not find any macrofossils of *Pinus* after 4000 cal. BP in the higher Lille Kjelavatn, but *Pinus* was most likely locally present at Isbenttjønn, since it is present today even though the pollen percentages in the surface sample reach their Holocene minimum (*Fig. 4.13*). The decreases in *Corylus*, *Ulmus*, *Tilia* and *Alnus* indicate that the source areas were further away (i.e., in lower elevations of the valley). Herb pollen increases only slightly, mainly caused by an increase in *Carex*-type pollen while fern spores increase due to increasing *Dryopteris*-type. *Sphagnum* also increases (spores and leaves, *Fig. 4.13, 4.14*). This suggests an expansion of wet areas in the catchment and/or mires at the lake banks. The first occurrences of *Plantago lanceolata* at 5,500 cal. BP together with increasing *Potentilla*-

type pollen suggests natural disturbances rather than human activity, since it is not accompanied by increased charcoal. During the period from 3,300 cal. BP until 1,400 cal. BP though (ITpz 3), the decrease in *Pinus* and the increases in charcoal and in herbs suggest human impact (*Fig. 4.13*). Presence of species like *Plantago lanceolata*, *Artemisia*, *Urtica* and increases in *Juniperus*, Poaceae and *Selaginella selaginoides* support this interpretation. Overall, a further opening of the *Betula-Pinus* woodland took place, with increasing percentages of herbaceous plants and a constant amount of ferns.

During the youngest period, from 1,400 cal. BP until present (ITpz 4), tree pollen decreases and herb pollen increases distinctly, while fern spores increase only slightly (*Fig. 4.13*). The decrease in trees is mainly due to a decrease in *Pinus*, suggesting that the local vegetation developed towards more open *Betula-Pine* woodland with *Betula* becoming more dominant. This resembles today's vegetation of open *Betula* forest with scattered *Pinus*. The opening of the landscape is also indicated by maxima of Poaceae, Cyperaceae undiff., and *Carex*-type. During this period, charcoal and *Calluna vulgaris* reach maximum values, indicating increased human impact. On the other hand, taxa like *Plantago lanceolata*, *Artemisia*, *Urtica* and *Potentilla* are constant and thus do not suggest an expansion of human impacted area. Thus though the vegetation became more open, human activity was most likely only moderate. However, the indicators for human impact support the assumption that the rejected radiocarbon date (I 954; *Fig. 4.5*) may contain old carbon related to reworked organic matter. *Sphagnum* spores indicate a further extension of mires around the lake, which is evident today by the existence of mires in the north-western corner of Isbenttjønn.

Conclusions

The ecological development of Reiarsdalsvatnet and Isbenttjønn and their catchments has been reconstructed on the basis of pollen and geochemical data. With regard to the main questions, the following conclusions are drawn:

1. Lake origin: Reiarsdalsvatnet and Isbenttjønn are both located in areas which became ice-free after the Younger Dryas glacial re-advance, but no specific information about the lake genesis is available. Damming of running water by glacio-fluvial deposits was most probably the cause for the development of Reiarsdalsvatnet. The genesis of Isbenttjønn is either connected to a shift of the course of the River Ralfdøla, or it is due to the development of a kettle lake.
2. Chronology: Even though radiocarbon dates of bulk organic matter of soft water lakes may show reservoir effects of a few hundred years (Björck *et al.* 1998, Oldfield *et al.* 1997), the chronologies of Reiarsdalsvatnet and Isbenttjønn and the results of the pollen data fit well to the known chronozones (*Fig. 4.11, 4.13*). The

onset of organic matter sedimentation and preservation occurred at 10,100 cal. BP (Reiarsdalsvatnet) and 9,300 cal. BP (Isbenttjønn).

3. Soil stability: As deduced from the lake sediments, soil stability in the catchments was reached c. 500 years after the onset of organic sediment formation in Reiarsdalsvatnet (9,600 cal. BP), and c. 700 years after the onset in Isbenttjønn (8,600 cal. BP). Thereafter, no erosional events are observed in the sediments.
4. Trophic status: Based on sedimentological proxies and pollen analyses, both lakes are classified as oligotrophic during the Holocene, but the lacustrine productivity was higher in Reiarsdalsvatnet than in Isbenttjønn. Both lakes show an increasing productivity in the youngest sediments. Mesohumic (Reiarsdalsvatnet) and meso- to polyhumic conditions (Isbenttjønn) are indicated by the sediments' C:N ratios and by the presence/absence of macrophytes. A tendency towards increasing dystrophication can be observed in the topmost sediments of Reiarsdalsvatnet and over most of the Isbenttjønn profile.
5. Catchment vegetation: The onset of the formation of organic sediment occurred in the Preboreal and Boreal chronozone for Reiarsdalsvatnet and Isbenttjønn, respectively. By 9,900 cal. BP, the region around Reiarsdalsvatnet was covered with a mixed deciduous-coniferous forest. *Betula-Pinus* woodland was present around Isbenttjønn after 9,300 cal. BP. An opening of the landscape started at 2,700 cal. BP at Reiarsdalsvatnet and at 1,400 cal. BP at Isbenttjønn, with increasing mire development in both catchments.
6. Human activity: At Reiarsdalsvatnet, elevated charcoal values as first signs of human activity are observed during the Middle Mesolithic. Thereafter, human activity is seen from 2,700 cal. BP at Reiarsdalsvatnet, and from 3,300 cal. BP at Isbenttjønn. Though human activity is indicated at both lakes during the last millennia, humans seem to have changed the vegetation around the lakes only gradually. No signs of agriculture are observed at Isbenttjønn and low numbers of *Hordeum*-type pollen in the Reiarsdalsvatnet record indicate that the growing of cereals was of minor importance.

Taking these conclusions into account, both lakes have undergone only minor changes during the Holocene. It was possible to reconstruct these changes independently from chironomid analyses. Thus both lakes should be suitable to reconstruct summer temperatures quantitatively based on the analysis of chironomid remains present in their sediments.

Chapter 5: Holocene successions of chironomid assemblages and their palaeoecological implications

Introduction

The analysis of chironomid assemblages has long been recognised as an important tool for the classification of lakes (Brundin 1949, Sæther 1975b, 1979, Thienemann 1913/14, Wiederholm 1980). These classification systems are designed for deep, thermally stratified lakes, where a distinct profundal chironomid community is developed and a few indicator species are primarily determined by oxygen and food availability (Brodersen and Quinlan 2006). However, profundal chironomid communities in deep lakes are not directly affected by changes in climate. Since climate is likely to have the strongest impact on relatively shallow lakes (Walker and Mathewes 1987b), these lakes are preferred for studies focussing on the reconstruction of temperature changes.

Shallow lakes are defined by the possibility to be colonised largely by macrophytes, by the absence of summer stratification (Scheffer 1998), and by not supporting a profundal chironomid community (Brodersen and Quinlan 2006). The presence of thermal summer stratification is dependent on the morphometric and limnological characteristics of the individual lake. Generally, stratification is poor if basin depths are less than 5 to 7 metres (Wetzel 2001). With today's maximum water depths of 9.2 m (Reiarsdalsvatnet) and 9.4 m (Isbenttjønn), it is assumed that both lakes can become thermally stratified, but that this stratification is not very stable or long lasting. The infilling of these lakes over the last c. 10,000 years had no major effects on the stratification regimes of the lakes because of relatively low sedimentation rates (*Fig. 4.3, 4.6*). Assuming a constant water table, the maximum water depths during the Holocene would not have exceeded 12.6 m (Reiarsdalsvatnet) and 11.6 m (Isbenttjønn), respectively. In addition, a large area of Reiarsdalsvatnet is less than 6 m deep (*Fig. 2.5*), and similar conditions most likely occur in Isbenttjønn. Since the typical Secci-disk transparency is greater than 5 m for oligotrophic lakes and 3 to 6 m for mesotrophic lakes (Håkanson and Jansson 1983), large areas of the lakes are expected to support the growth of macrophytes. Because of these morphometric characteristics, Reiarsdalsvatnet and Isbenttjønn are not regarded as typical shallow lakes, but as lakes at a transition from dimictic to typically shallow lakes. Thus it is expected that littoral and sublittoral chironomid taxa are of greater importance than profundal taxa in Reiarsdalsvatnet and Isbenttjønn.

In this Chapter, the development of subfossil chironomid assemblages over the last c. 10,000 years in Reiarsdalsvatnet and Isbenttjønn is studied. The chironomid assemblages are interpreted qualitatively and are discussed against the background of the pollen and geochemical data presented in Chapter 4. The aim is to characterise the lakes' palaeoecological development on the basis of the chironomid analyses and to find out how sensitive the chironomid fauna responded to the small-scale changes in environmental conditions, which have been reconstructed in Chapter 4.

Results

Chironomid analyses

For Reiarsdalsvatnet an average of 86 head-capsules (hc) per sample was identified with 93 % of the samples containing 70 or more head-capsules. Since the head-capsule concentration is significantly lower in sediments from Isbenttjønn, only 48 % of these samples contain more than 70 head-capsules. Still, a mean of 71 head-capsules was identified and 93 % of the samples had more than 50 head-capsules. It has been shown by different studies that quantitative environmental reconstructions based on 50 head-capsules per sample give reliable results (Heiri and Lotter 2001, Larocque 2001, Quinlan and Smol 2001).

The results of chironomid analysis are presented as percentage data (*Fig. 5.1, 5.5*) and influx rates (*Fig. 5.2, 5.6*). The given ages are rounded to the nearest 100 years to account for the uncertainties of the age-depth models (*Fig. 4.2, 4.5*). The formation of simple ecological indices (*Fig. 5.3, 5.4, 5.7, 5.8*) accounts for the fact that littoral chironomid taxa often have a wide ecological range and thus specific indicator taxa are few (Brodersen and Quinlan 2006). As mentioned in Chapter 3, specific ecological information was not available for all chironomid taxa identified in this study. This results in the percentage indices not summing to 100 %.

Reiarsdalsvatnet

No chironomid head-capsules were found in the samples below 338 cm sediment depth (10,200 cal. BP). In the record younger than 10,200 cal. BP, five statistically significant local chironomid assemblage zones (RVchz 1 to RVchz 5) were identified (*Fig. 5.1*). To facilitate description and discussion, the percentage-data-based zonation was transferred to the graphs of the influx data (*Fig. 5.2*) and of the ecological indices (*Fig. 5.3, Fig. 5.4*).

Head-capsule influx determined by means of adding microspheres to the sample material during the separation of head-capsules from the sediment were omitted. These influx rates were considerably higher than the influx calculation based on the separation of all head-capsules from the weighed sediment sample (max: 250 %, mean 132 %, n = 20). Because of this bias, only head-capsule influx rates determined by separating all head-capsules from a sample are shown for Reiarsdalsvatnet (*Fig. 5.2, 5.4*, 20 samples).

RVchz 1: 10,200 – 10,000 cal. BP

RVchz 1 is characterised by *Stictochironomus*, *Heterotrissocladius maeri*-type, *Microtendipes*, *Micropsectra insignilobus*-type, and Tanytarsini 'no spur' (*Fig. 5.1*), and a very low influx of chironomid head-capsules (*Fig. 5.2*). The ecological indices show that chironomids preferring lentic habitats in oligotrophic lakes, mainly belonging to the collector-feeding group, dominate in this phase (*Fig. 5.3*).

RVchz 2: 10,000 – 9,000 cal. BP

Total head-capsule influx rates around 20,000 hc m^{-2} a^{-1} are reached in RVchz 2 (*Fig. 5.2*). *Microtendipes* and Tanytarsini 'no spur' are dominant with percentages exceeding 20 % (*Fig. 5.1*). Other important taxa are *Tanytarsus lugens*-type, *Heterotrissocladius grimshawi*-type, and Tanytarsini indet. The first occurrences of *Procladius*, *Eukiefferiella*, *Ablabesmyia*, and *Psectrocladius sordidellus*-type, which are present throughout the rest of the Holocene, are in this assemblage zone. *Stictochironomus* and *Heterotrissocladius maeri*-type decline and are not present any more later on. The species turnover indicates that the largest changes in the chironomid assemblages between two successive samples occur in RVchz 2 (*Fig. 5.1*). The share of chironomid taxa preferring lotic environments increases in the course of RVchz 2 (*Fig. 5.3*). In the taxa preferring lentic environments, littoral taxa increase in comparison to profundal taxa. While the percentage-based indices point to a decrease in oligotrophic taxa in RVchz 2 (*Fig. 5.3*), the influx index reveals that the number of taxa characteristic of oligotrophic conditions does not decrease during this phase (*Fig. 5.4*). First appearances in low numbers of taxa occurring in mesotrophic, eutrophic, and meso-/ polyhumic lakes are present. Collectors are the most important-feeding group, but predators occur in increasing numbers and scrapers appear for the first time.

RVchz 3: 9,000 – 7,000 cal. BP

Up to 28 % *Heterotanytarsus apicalis*-type and 27 % *Sergentia* characterise RVchz 3 (*Fig. 5.1*). *Heterotrissocladius marcidus*-type, *Ablabesmyia*, and *Psectrocladius sordidellus*-type are subdominant during this phase, and *Tanytarsus lugens*-type, *Microtendipes*, and Tanytarsini 'no spur' decline distinctly during the first half of RVchz 3. The influx of chironomid taxa preferring lotic environments reaches the value that then stays almost constant throughout the rest of the profile (*Fig. 5.4*).

Figure 5.1: Chironomid percentage diagram of selected taxa [%] sorted by their weighted average with depth, species turnover (DCA axis 1 sample scores [SD]), and local chironomid assemblage zones (RVchz) for Reiarsdalsvatnet.

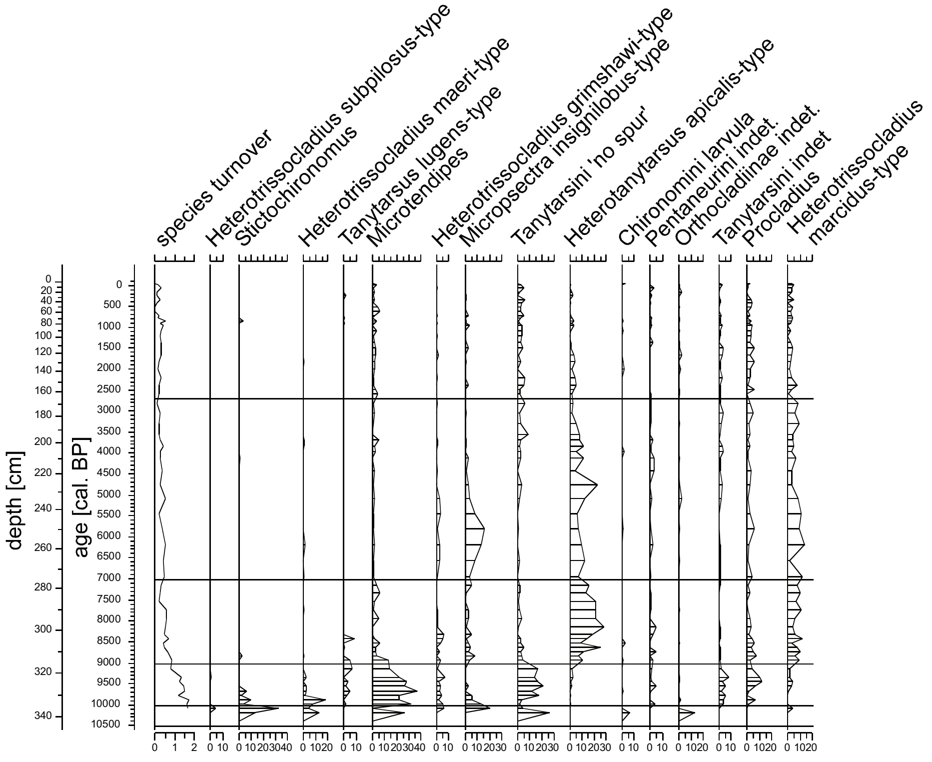
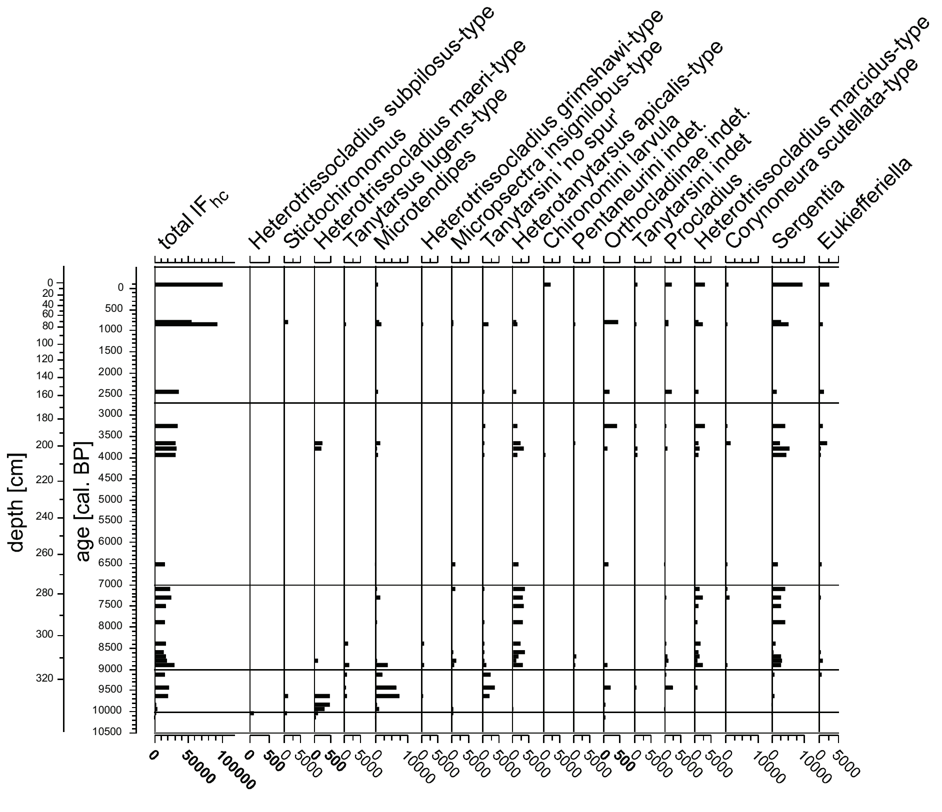


Figure 5.2: Total chironomid head-capsule influx (IF_{hc}) and influx of selected taxa [hc (m^2 a)$^{-1}$] sorted by their weighted average with depth and local chironomid assemblage zones (RVchz) for Reiarsdalsvatnet. Only 20 samples are included due to methodological uncertainties in the determination of head-capsule (hc) concentration in the samples not shown. Note the different scale of the bold x-axis values.



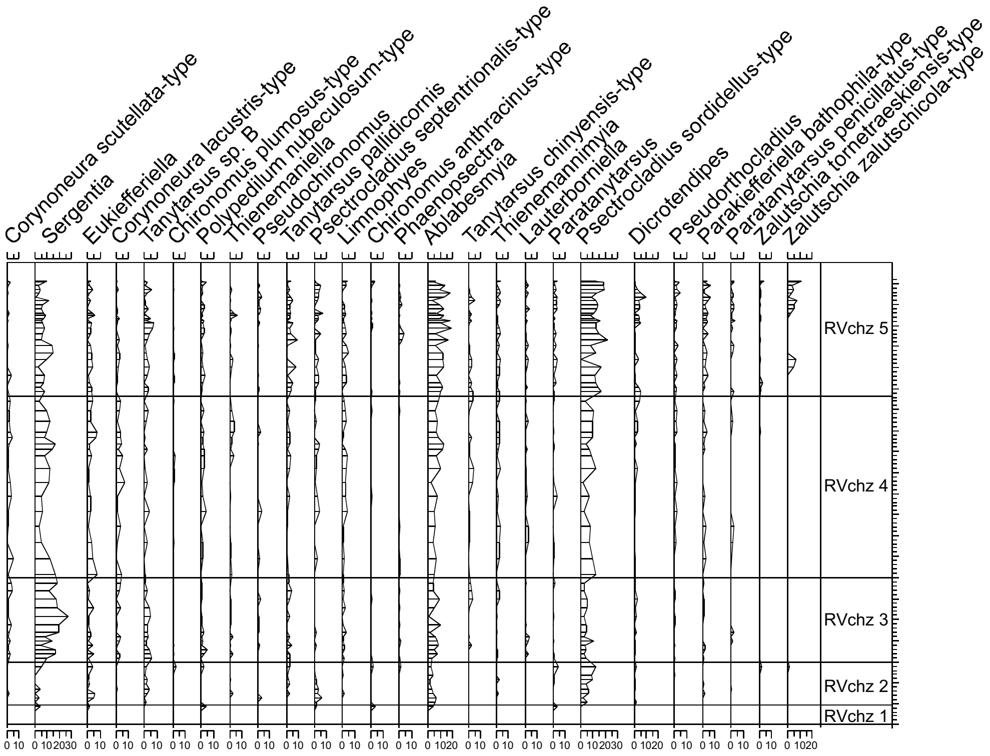


Figure 5.1: - continued –

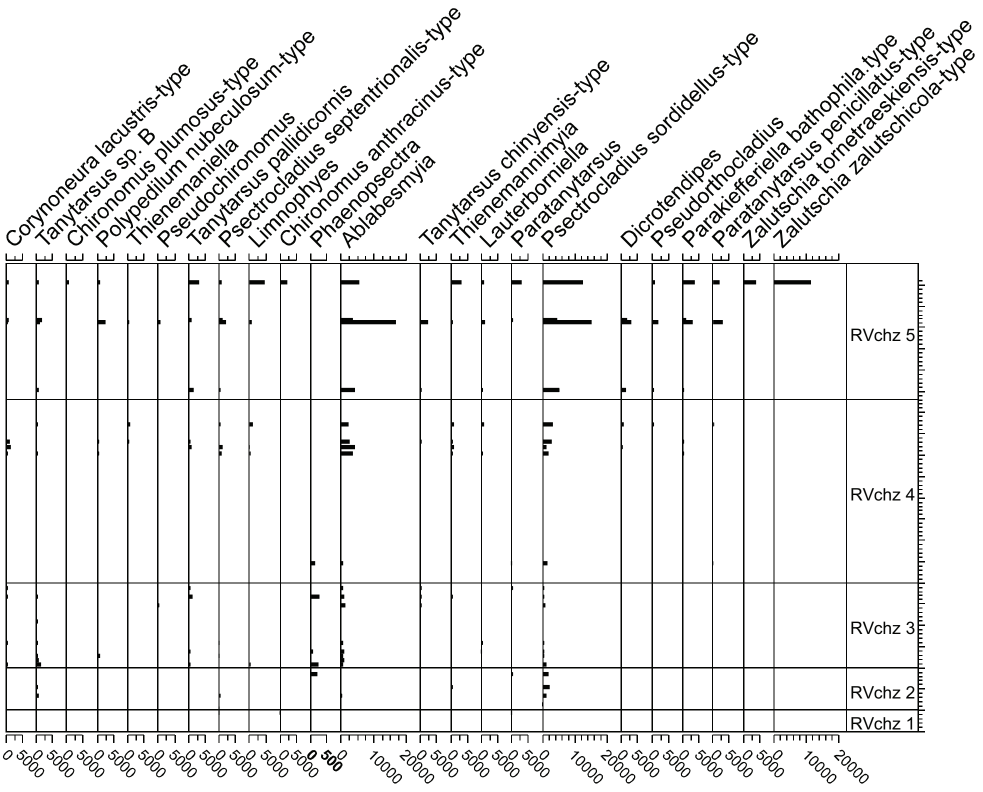


Figure 5.2: - continued -

Littoral taxa influxes show values comparable to RVchz 2, while profundal taxa increase in RVchz 3 (*Fig. 5.4*). Taxa mainly occurring in oligotrophic environments are dominant and an onset of taxa present in meso-/ polyhumic environments can be observed in RVchz 3 (*Fig. 5.3, 5.4*). Scrapers increase with the beginning of RVchz 3 and filter feeders occur in low numbers (*Fig. 5.3, 5.4*).

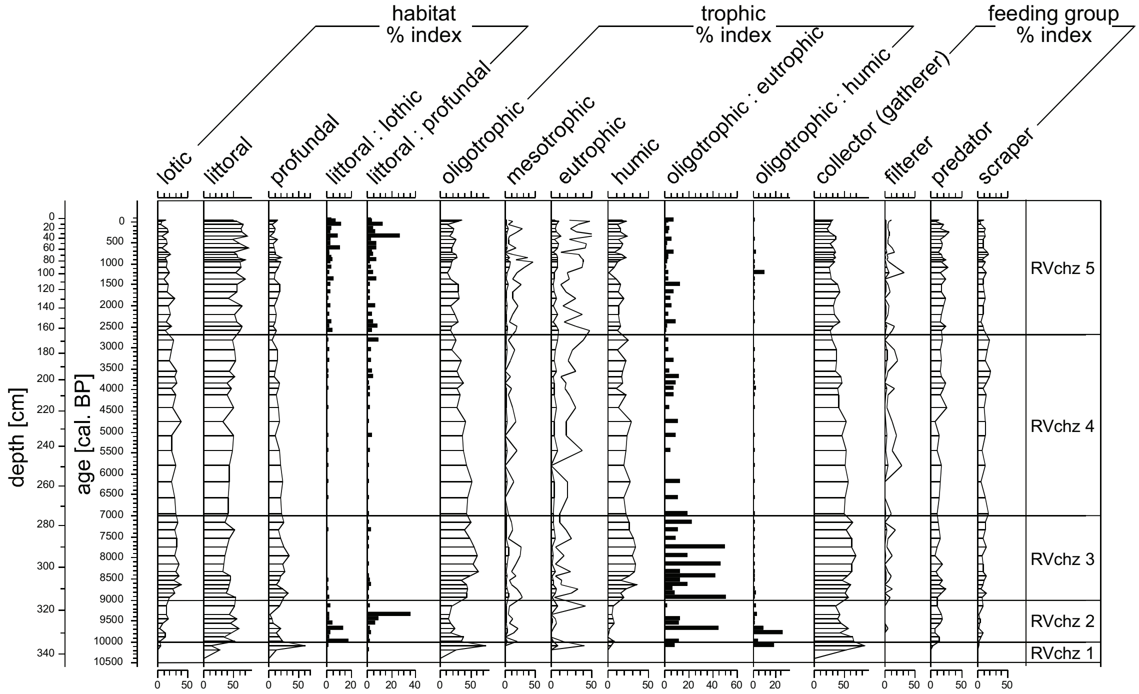


Figure 5.3: Ecological indices based on chironomid percentage data (silhouettes) and selected ratios of these (bars) for Reiarsdalsvatnet. The hollow silhouettes denote a 5-fold exaggeration of the original values.

RVchz 4: 7,000 – 2,700 cal. BP

With maximum values between 10 % and 20 %, *Micropsectra insignilobus*-type, *Heterotanytarsus apicalis*-type, *Heterotrissocladius marcidus*-type, *Sergentia*, *Ablabesmyia*, and *Psectrocladius sordidellus*-type are the most important taxa in RVchz 4 (*Fig. 5.1*). *Micropsectra insignilobus*-type dominates the older part of this phase until 5,000 cal. BP, when it declines distinctly. Total influx reaches values above 30,000 hc m^{-2} a^{-1} around 4,000 cal. BP (*Fig. 5.2*).

With regard to the ecological indices, RVchz 4 is the continuation of RVchz 3, with only minor changes between them (*Fig. 5.3, 5.4*). The littoral:profundal ratio suggests slowly growing importance of littoral taxa, while decreasing oligotrophic:eutrophic ratios hint towards increasing percentages of chironomid taxa that prefer a higher nutrient status. Still, the indicators for oligotrophy are dominant (*Fig. 5.3, 5.4*). No changes can be seen in the feeding preferences compared to RVchz 3.

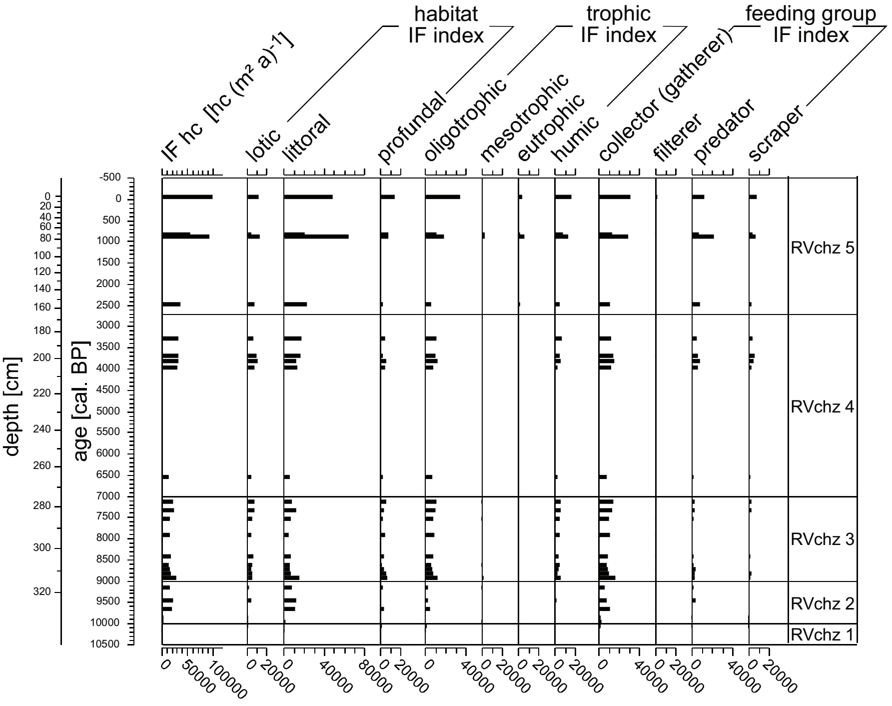


Figure 5.4: Ecological indices based on chironomid influx (IF [hc (m² a)$^{-1}$]) data for Reiarsdalsvatnet. Only 20 samples are included due to methodological uncertainties in the determination of head-capsule (hc) concentration in the samples not shown.

RVchz 5: 2,700 cal. BP to present

Maximum total influx rates exceeding 50,000 hc m^{-2} a^{-1} are found in RVchz 5 (*Fig. 5.2*). The dominance of *Sergentia*, *Ablabesmyia*, and *Psectrocladius sordidellus*-type are distinct in both percentage and influx data (*Fig. 5.1, 5.2*). *Heterotanytarsus apicalis*-type decreases, while *Parakiefferiella bathophila*-type increases. *Dicrotendipes* and *Zalutschia zalutschicola*-type become increasingly important after 1,000 cal. BP, which is reflected in decreasing species turnover (*Fig. 5.1*). The ecological indices show that taxa from littoral environments become increasingly important towards the sediment surface (*Fig. 5.3, 5.4*). Oligotrophic:eutrophic ratios are lowest in RVchz 5, indicating a further increasing importance of eutrophy-indicating taxa, even though taxa characteristic of oligotrophic environments are still dominant. Oligotrophic:meso-/ polyhumic ratios are constant from RVchz 3 to RVchz 5, indicating constant values in taxa characteristic of meso-/ polyhumic conditions. With regard to the feeding preferences, the proportions of the four groups are almost constant throughout RVchz 3 to RVchz 5.

Isbenttjønn

The chironomid profile of Isbenttjønn shows little change during the Holocene (*Fig. 5.5*), but three significant local chironomid assemblage zones (ITchz 1 to ITchz 3) are distinguished.

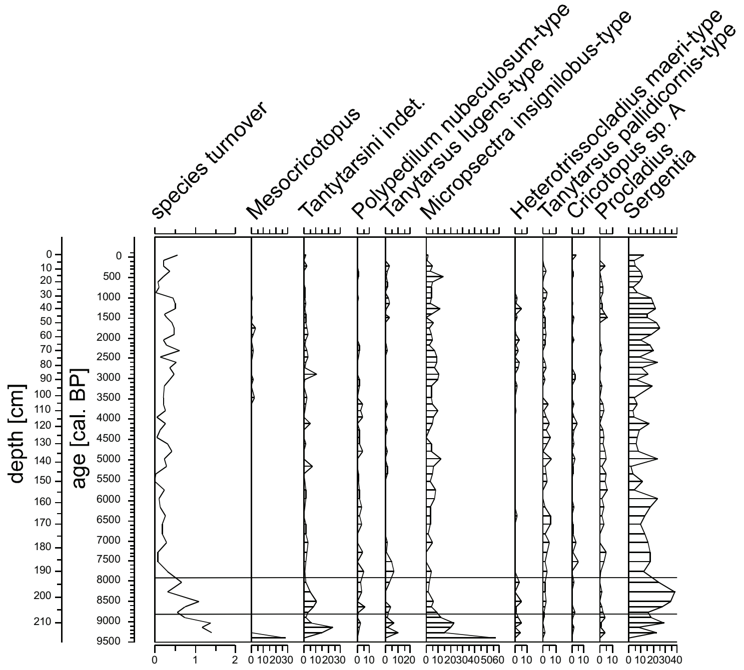


Figure 5.5: Chironomid percentage diagram of selected taxa [%] sorted by their weighted average with depth, species turnover (DCA axis 1 sample scores [SD]), and local chironomid assemblage zones (ITchz) for Isbenttjønn.

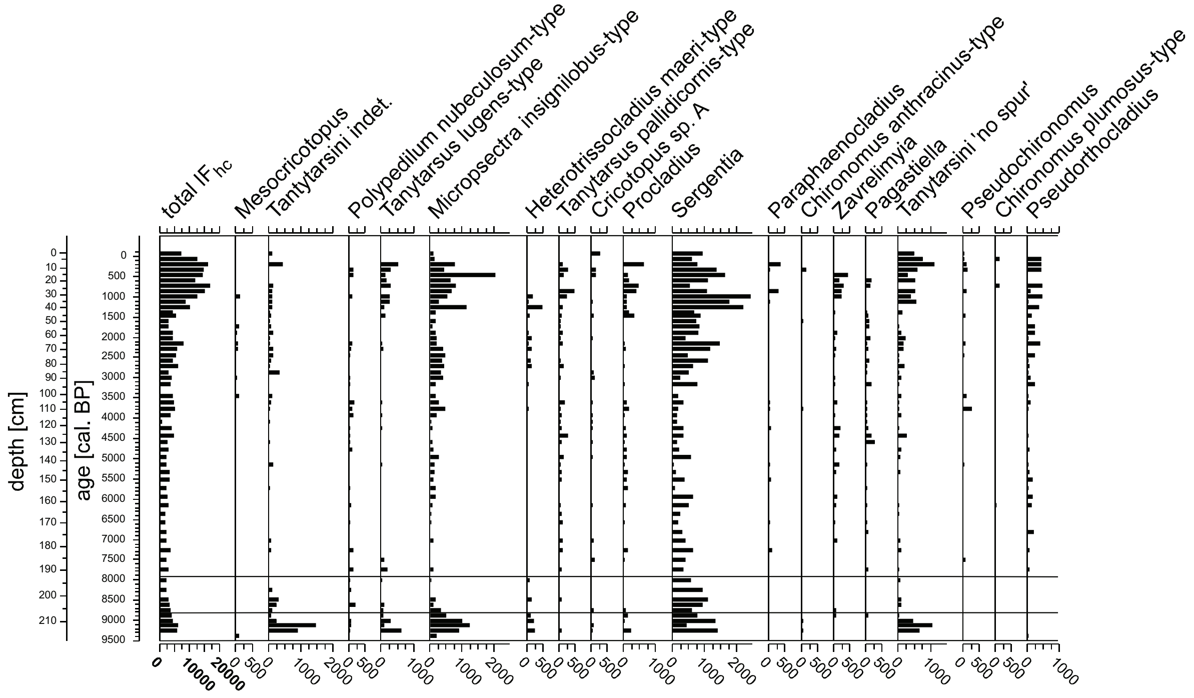


Figure 5.6: Total chironomid head-capsule influx (IF_{hc}) and influx of selected taxa [hc (m^2 a)$^{-1}$] sorted by their weighted average with depth, and local chironomid assemblage zones (ITchz) for Isbenttjønn. Note the different scale of the bold x-axis values.

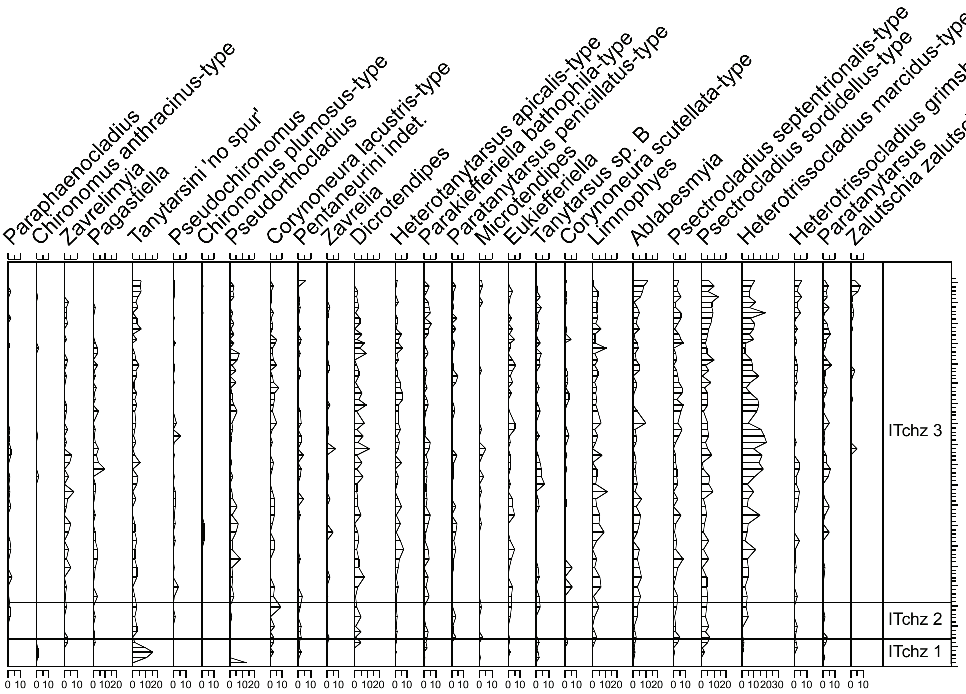


Figure 5.5: - continued –

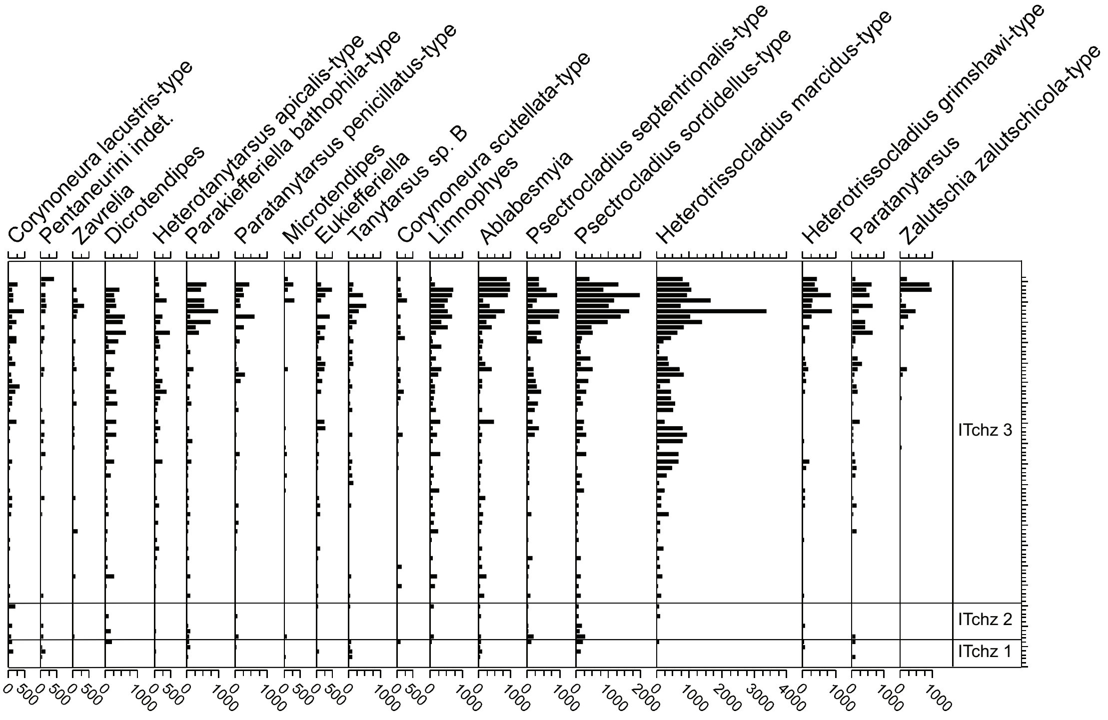


Figure 5.6: - continued –

ITchz 1: 9,400 – 8,800 cal. BP

ITchz 1 is characterised by very low total influx rates in the oldest sample followed by a local influx maximum of more than 6,000 hc m^{-2} a^{-1} (*Fig. 5.6*). Most important taxa are *Tanytarsus lugens*-type, *Micropsectra insignilobus*-type, *Sergentia*, Tanytarsini indet., and Tanytarsini 'no spur' (*Fig. 5.5*). The high percentages of the latter two might indicate poor preservation conditions for chironomid head-capsules. Ecologically, this assemblage zone is characterised by a high share of taxa preferring profundal environments (*Fig. 5.7*). Lotic and littoral taxa are present in smaller numbers (*Fig. 5.8*). Taxa characteristic of oligotrophic conditions dominate and collectors are the most important feeding group (*Fig. 5.7, 5.8*).

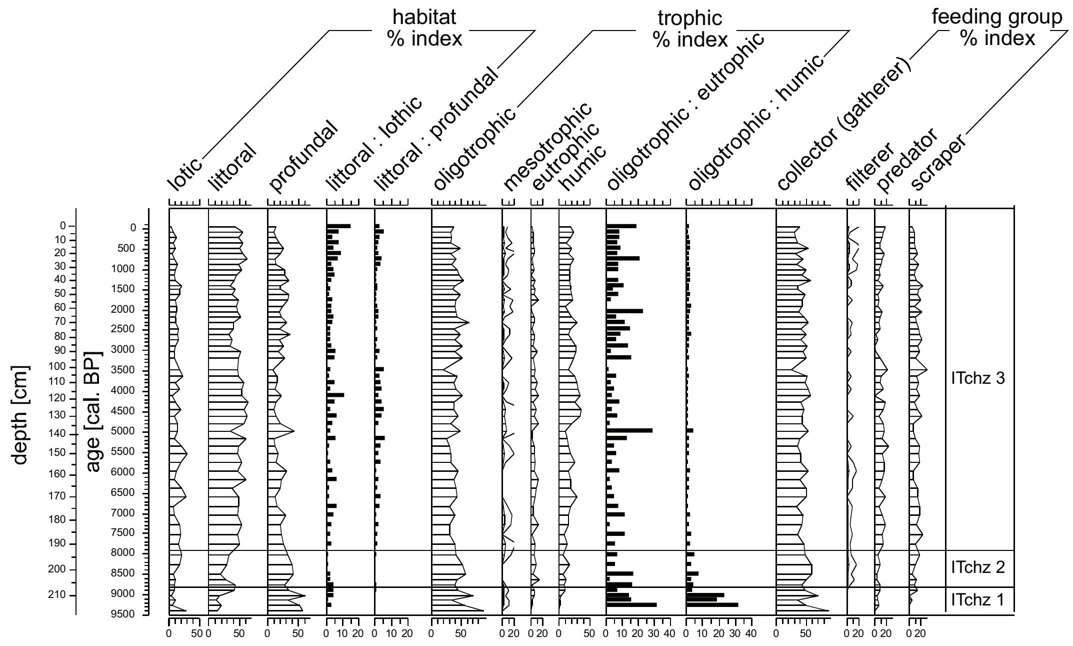


Figure 5.7: Ecological indices based on chironomid percentage data (silhouettes) and selected ratios of these (bars) for Isbenttjønn. The hollow silhouettes denote a 5-fold exaggeration of the original values.

ITchz 2: 8,800 – 7,900 cal. BP

ITchz 2 is dominated by *Sergentia* (*Fig. 5.5*). Tanytarsini indet., the onset of *Dicrotendipes*, *Psectrocladius sordidellus*-type and *Heterotrissocladius marcidus*-type, and the decrease of *Tanytarsus lugens* and *Micropsectra insignilobus*-type are other characteristic features of this assemblage zone and species turnover decreases in ITchz 1 and 2 (*Fig. 5.5*).

Taxa preferring profundal environments and indices for oligotrophic conditions decrease in ITchz 2 (*Fig. 5.7*). The influx of lotic and littoral taxa remains similar to

ITchz 1 (*Fig. 5.8*). Taxa characteristic of meso-/ polyhumic conditions increase and the onset of the occurrence of filter feeders and an increase of scrapers occur in ITchz 2.

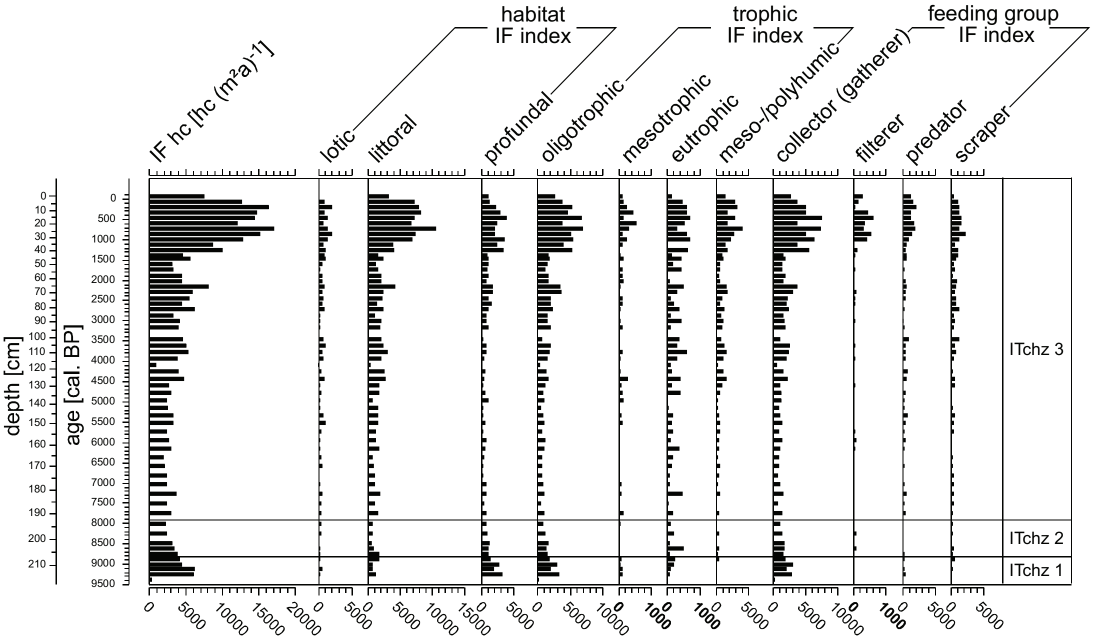


Figure 5.8: Ecological indices based on chironomid influx (IF [hc (m² a)⁻¹]) data for Isbenttjønn. Note the different scale of the bold x-axis values.

ITchz 3: 7,900 cal. BP to present

Sergentia and *Heterotrissocladius marcidus*-type dominate ITchz 3 (*Fig. 5.5*). Other important taxa are *Micropsectra insignilobus*-type, Tanytarsini 'no spur', *Dicrotendipes*, *Limnophyes*, *Ablabesmyia*, and *Psectrocladius sordidellus*-type. Species overturn shows little change. Total influxes generally increase to the sediment top with distinctly increasing values after 1,300 cal. BP (*Fig. 5.6*). At the beginning, these high values are mainly due to high influxes of *Sergentia*, while after 900 cal. BP *Sergentia* decreases and *Heterotrissocladius mancus*-type and *Psectrocladius sordidellus*-type become more important. The onset of *Zalutschia zalutschicola*-type can be seen around 900 cal. BP (*Fig. 5.6*). *Zalutschia zalutschicola*-type increases to the sediment top as does *Ablabesmyia*. At the transition from ITchz 2 to ITchz 3, the littoral:profundal ratio increases (*Fig. 5.7*), indicating a growing importance of taxa preferring littoral environments. The influx of lotic taxa is almost constant throughout the profile (*Fig. 5.8*). Indices for trophic state show stable conditions throughout ITchz 3 with a dominance of taxa characteristic of oligotrophic or meso-/ polyhumic conditions. With regard to feeding groups, the proportions of the different groups resemble those in ITchz 2 and remain constant with the exception of increasing filter feeders after 900 cal. BP.

Non-chironomid remains

In addition to subfossil chironomid remains, larval mandibles and head-capsules of other Diptera (Chaboridae, Simuliidae, Ceratopogonidae), and remains of Ephemeroptera, Plecoptera, and Trichoptera from the sediments of Isbenttjønn were identified (*Fig. 5.9*). The influx values of non-chironomid remains are comparable to those of single chironomid taxa in Isbenttjønn. Non-chironomid remains are present from ITchz 1 onwards. Until c. 8,500 cal. BP Ceratopogonidae are dominant. They are superseded in dominance by *Chaoborus flavicans* and Ephemeroptera by c. 8,500 cal. BP. A major change occurred between 1,400 cal. BP and 1,200 cal. BP, when *Chaoborus flavicans* declines distinctly and Ceratopogonidae increases, which is evident from the percentage and the influx data (*Fig. 5.9*). During this phase, Ephemeroptera shows decreasing percentages but no change in their influx values. Thus the decrease in Ephemeroptera percentages is only due to the increase in chironomid head-capsules influx (*Fig. 5.6*).

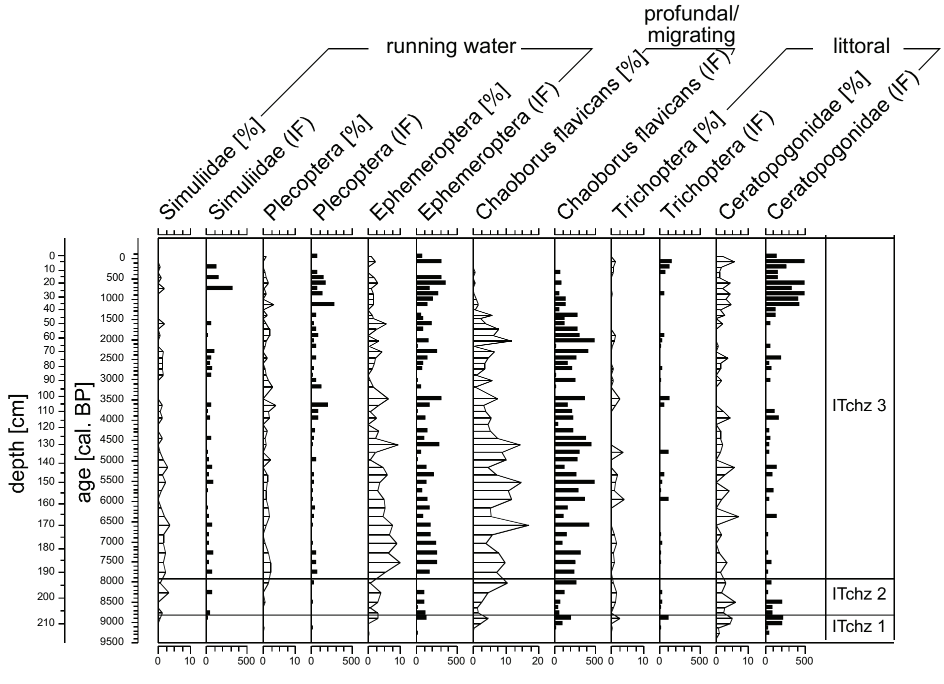


Figure 5.9: Percentages [%] (silhouettes) and influx [hc $(cm^2\,a)^{-1}$] (bars) of non-chironomid faunal remains for Isbenttjønn, grouped by their typical habitats.

Ordination

The short first DCA axes (*Tab. 5.1*) suggests the use of linear-based ordination methods (Lepš and Šmilauer 2003) and PCA was chosen as the appropriate method to reveal the underlying structures in the chironomid data-sets. In both data-sets, the respective oldest sample was omitted for ordination, since they contain less than 10 head-capsules. Both samples are outliers in the numerical analyses because of the low total number rather than because of substantial differences in their assemblages. A summary of the analyses is shown in *Table 5.1*. Sample scores are presented as Euclidian distance scatter plots, and species scores in correlation scatter plots (*Fig. 5.10, 5.12*). In addition, stratigraphic plots of the sample scores are shown (*Fig. 5.11, 5.13*)

Table 5.1: Summary of the results of the detrended correspondence analyses (DCA) and the principal component analyses (PCA) of the chironomid percentage data for Reiarsdalsvatnet and Isbenttjønn. The analysis 'PCA Isbenttjønn II' is only based on samples inferring ‚reliable' temperatures. For additional information see Chapter 6 and Table A3. *Statistically significant PCA axes (bold numbers) are assessed by comparison with the broken-stick model (Bennett 1996).*

DCA Reiarsdalsvatnet					
Number of samples	63				
Number of species	107				
Axes	1	2	3	4	Total inertia
Eigenvalues	0.162	0.076	0.046	0.038	1.305
Lengths of gradient	1.736	1.215	1.073	1.226	
Cumulative percentage variance of species data	12.4	18.2	21.8	24.7	

DCA Isbenttjønn					
Number of samples	57				
Number of species	102				
Axes	1	2	3	4	Total inertia
Eigenvalues	0.084	0.064	0.051	0.04	1.162
Lengths of gradient	1.406	1.594	1.095	1.059	
Cumulative percentage variance of species data	7.3	12.8	17.1	20.6	

PCA Reiarsdalsvatnet					
Number of samples	63				
Number of species	107				
Axes	1	2	3	4	Total variance
Eigenvalues	**0.166**	**0.134**	**0.059**	0.042	1
Cumulative percentage variance of species data	16.6	30	35.9	40.1	

PCA Isbenttjønn					
Number of samples	57				
Number of species	102				
Axes	1	2	3	4	Total variance
Eigenvalues	**0.115**	**0.07**	**0.061**	0.051	1
Cumulative percentage variance of species data	11.5	18.4	24.5	29.7	

PCA Isbenttjønn II					
Number of samples	42				
Number of species	95				
Axes	1	2	3	4	Total variance
Eigenvalues	**0.131**	0.074	0.065	0.059	1
Cumulative percentage variance of species data	13.1	20.6	27.1	33	

Reiarsdalsvatnet

The eigenvalues of the first three PCA axes (*Tab. 5.1*) are larger than expected by comparison with the broken-stick model (Bennett 1996) and are thus assumed to be statistically significant. They explain 35 % of the variance in the species data. Changes along the first PCA axis (*Fig. 5.10, 5.11*) are responsible for the separation between samples of RVchz 1 and 2, and samples of RVchz 3, 4, and 5. Regarding the trajectories and the species scores, this characterises a succession from an assemblage dominated by Tanytarsini 'no spur', *Microtendipes*, *Heterotrissocladius maeri*-type, and *Stictochironomus* to one where these taxa are only present in low numbers and where *Sergentia* plays a major role (*Fig. 5.10*). The second PCA axis shows a general development from RVchz 3 to RVchz 5 characterised by increasing sample scores with decreasing age (*Fig. 5.11*). A succession along PCA axis 2 from dominant *Heterotanytarsus apicalis*-type and *Micropsectra insignilobus*-type to assemblages dominated by *Psectrocladius sordidellus*-type and *Zalutschia zalutschicola*-type is apparent (*Fig. 5.10*). PCA axis 3 reveals changes in the RVchz 1 and 2 sample scores and stable sample scores in the younger sediments (*Fig. 5.11*).

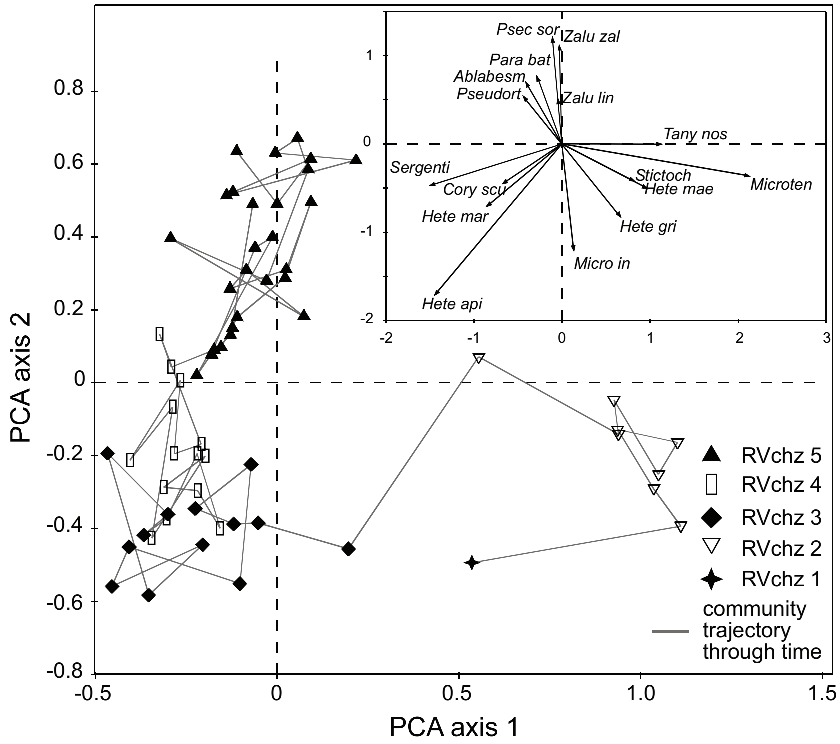


Figure 5.10: Euclidian distance scatter plot of the principal component analysis (PCA) sample scores (first and second axis) for the Reiarsdalsvatnet chironomid percentage data. Local chironomid assemblage zones are marked by symbols. A correlation scatter plot of selected taxa is presented in the inset. For abbreviations see Table A1.

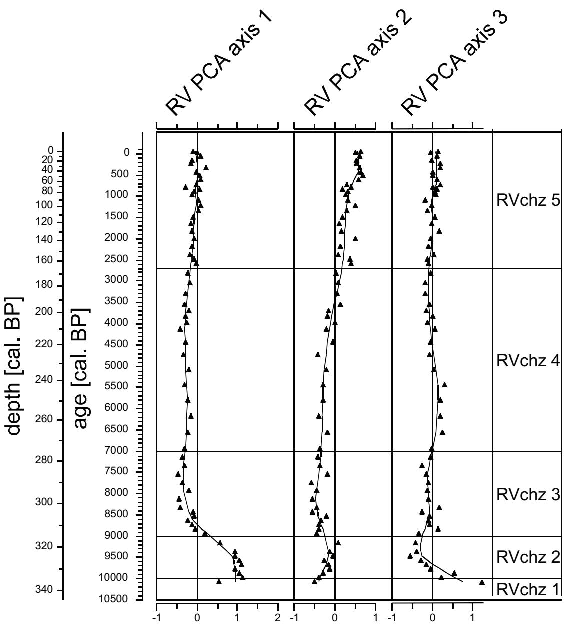


Figure 5.11: Stratigraphic plots of sample scores of the first, second, and third axes principal component analysis (PCA) for Reiarsdalsvatnet chironomid percentage data. The century-scale trends are highlighted by a LOWESS smoother (span: 0.2).

Isbenttjønn

As at Reiarsdalsvatnet, the first three PCA axes (*Tab. 5.1*) for the Isbenttjønn chironomid data-set are larger than expected by comparison with the broken-stick model and are thus assumed to be statistically significant. *Figure 5.12* shows that no clear succession with time is indicated from the trajectory. The first PCA axis divides ITchz 1and 2 from ITchz 3 (*Fig. 5.13*) with Tanytarsini indet., *Micropsectra*, and *Heterotrissocladius maeri*-type dominating the first group and *Heterotrissocladius marcidus*-type the second one (*Fig. 5.12*). ITchz 3 sample scores show a high variability on PCA axis 2 with no a clear age-dependence (*Fig. 5.13*). Only samples younger than 1,300 cal. BP are distinctly characterised by high scores on PCA axis 2. *Dicrotendipes*, *Pagastiella*, *Tanytarsus palidicornis*-type and *Heterotanytarsus apicalis*-type account for low sample scores on this axis, while *Heterotrissocladius grimshawi*-type, Tanytarsini indet., and *Ablabesmyia* are typical for samples with high PCA axis 1 scores (*Fig. 5.12*). Sample scores on PCA axis 3 also show high variability between samples and fluctuate around 0 throughout the main part of the profile, with one distinct change apparent around 3,600 cal. BP, where sample scores change from negative to positive values (*Fig. 5.13*).

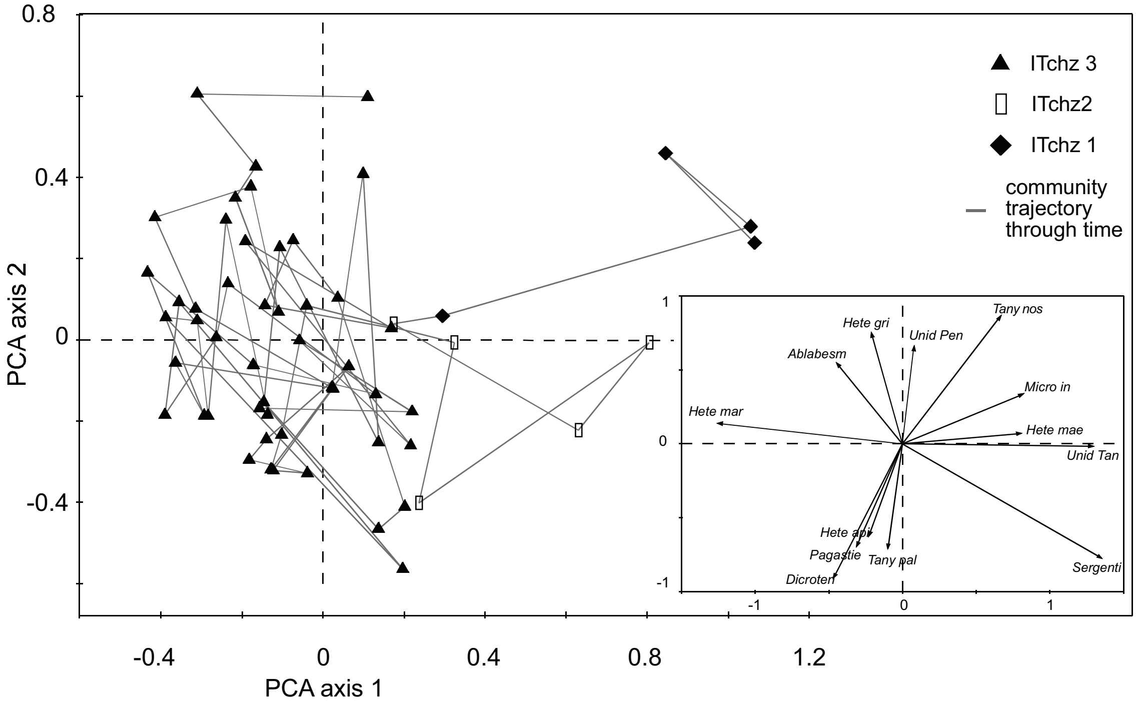


Figure 5.12: Euclidian distance scatter plot of the principal component analysis (PCA) sample scores (first and second axis) for the Isbenttjønn chironomid percentage data. Local chironomid assemblage zones are marked by symbols. A correlation scatter plot of selected taxa is presented in the inset. For abbreviations see Table A1.

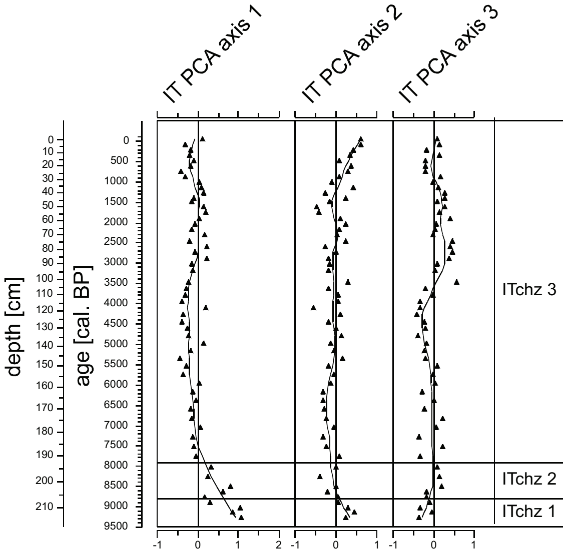


Figure 5.13: Stratigraphic plots of sample scores of the first, second, and third axes principal component analysis (PCA) for Isbenttjønn chironomid percentage data. The century-scale trends are highlighted by a LOWESS smoother (span: 0.2).

Rate-of-change analyses

Rates of change were calculated for pollen and chironomid percentage data of both lakes and are presented stratigraphically (*Fig. 5.14, 5.15*). In the first step, rates of change per 150 years were calculated without any interpolation between samples. The correlation of these rates of change (marked with (A) in *Figures 5.14* and *5.15*) and the time intervals between consecutive samples (sample resolution [a]) is highly significant for chironomids (Spearman rank correlation coefficient of $r = -0.94$ for RV and $r = -0.78$ for IT; $p < 0.05$) and pollen ($r = -0.95$ for RV and $r = -0.88$ for IT; $p < 0.05$). To account for this dependence, a linear interpolation was implemented in a second step (Laird *et al.* 1998), (marked with (B) in *Figures 5.14* and *5.15*). Interpolation intervals of 150 years were chosen for chironomids and pollen in both lakes, due to the mean length of time intervals between samples, which are minimal 115 years (RV pollen) and maximal 166 years (IT chironomids).

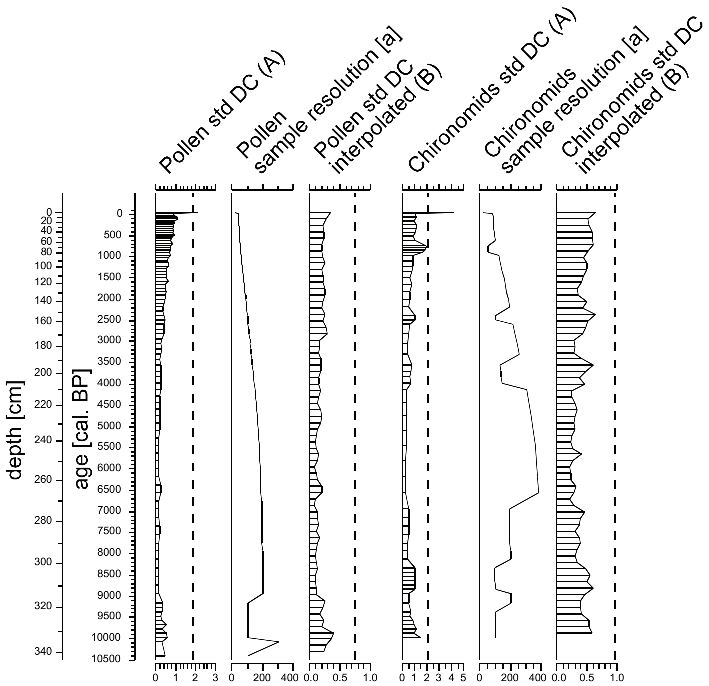


Figure 5.14: Sample scores of the rate-of-change analysis for pollen and chironomid percentage data for Reiarsdalsvatnet (std DC: chord dissimilarity coefficient, standardised to 150 years). Graphs marked with (A) are calculated without interpolation, the ones marked with (B) are calculated with linear interpolated sample intervals of 150 years. Dashed lines show the 95 percentile of the permutation test, indicating statistical significance.

Compared to the 95 percentile of the permutation test, only single samples of the non-interpolated data show significant rates of change ((A) in *Figures 5.14* and *5.15*). The significance of these values are due to the bias caused by unequal sample intervals and are not apparent, when calculating the rates-of-change from interpolated data ((B) in Figures *5.11* and *5.12*). In the latter analysis, no sample interval reaches values above the 95 percentile of the permutation test, thus the rates-of-change in the analysed profiles are not statistically significant.

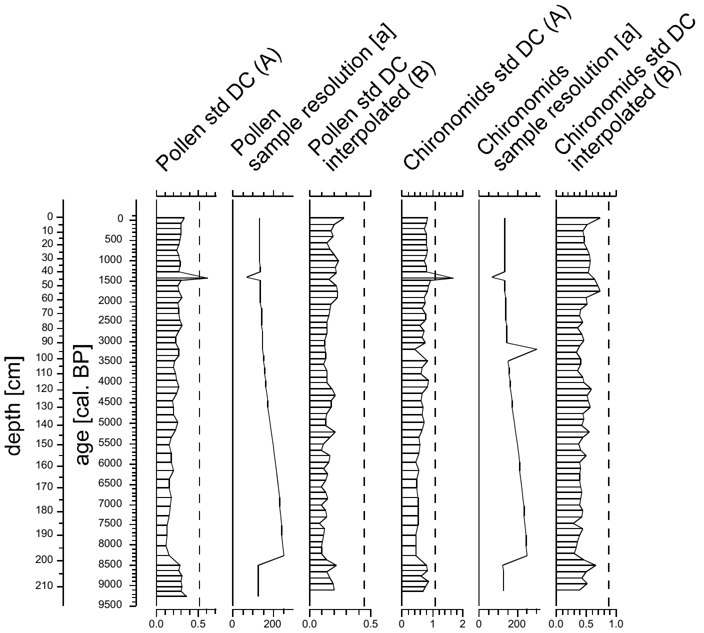


Figure 5.15: Sample scores of the rate-of-change analysis for pollen and chironomid percentage data for Isbenttjønn (std DC: chord dissimilarity coefficient, standardised to 150 years). Graphs marked with (A) are calculated without interpolation, the ones marked with (B) are calculated with linear interpolated sample intervals of 150 years. Dashed lines show the 95 percentile of the permutation test, indicating statistical significance.

Interpretation and discussion

Palaeoecological development during the Holocene

Reiarsdalsvatnet

A profundal chironomid fauna, which is dominated by *Sergentia* and in the oldest part by *Stictochironomus* and *Micropsectra insignilobus*-type, is present in Reiarsdalsvatnet throughout the Holocene (*Fig. 5.1*). According to Wiederholm (1980) and Sæther (1979), these profundal taxa are indicators of oligo- to mesotrophic lakes. This is supported by the ecological sum indices, suggesting that Reiarsdalsvatnet was mainly oligotrophic during the studied period with a slightly increasing nutrient status with decreasing age (*Fig. 5.3*). The existence of a profundal chironomid fauna supports the morphometry-based assumption that the lake becomes thermally stratified in summers. Even though this indicates that Reiarsdalsvatnet is not a typical shallow lake, the direct relation to climate influences is given since chironomid taxa preferring littoral environments form the majority of the chironomids since 10,000 cal. BP (*Fig. 5.3*). With the abundance of *Sergentia*, which is characteristic of moderate oxic conditions (Little *et al.* 2000), and the near absence of *Chironomus*, strongly associated with low oxygen levels (Warwick 1975, Wiederholm and Eriksson 1979), it is suggestive that good to moderate hypolimnetic oxygen conditions prevailed in Reiarsdalsvatnet throughout the Holocene. This confirms the finding of low sulphur contents in the sediment (*Fig. 4.9*), which has been interpreted as a sign of hypolimnetic oxygen availability (Chapter 4). Stable influx of lotic taxa since 9,000 cal. BP (*Fig. 5.3*) suggests the absence of major changes in the inflow into Reiarsdalsvatnet, which supports the assumption of stable conditions in the catchment after 8,900 cal. BP as discussed in Chapter 4.

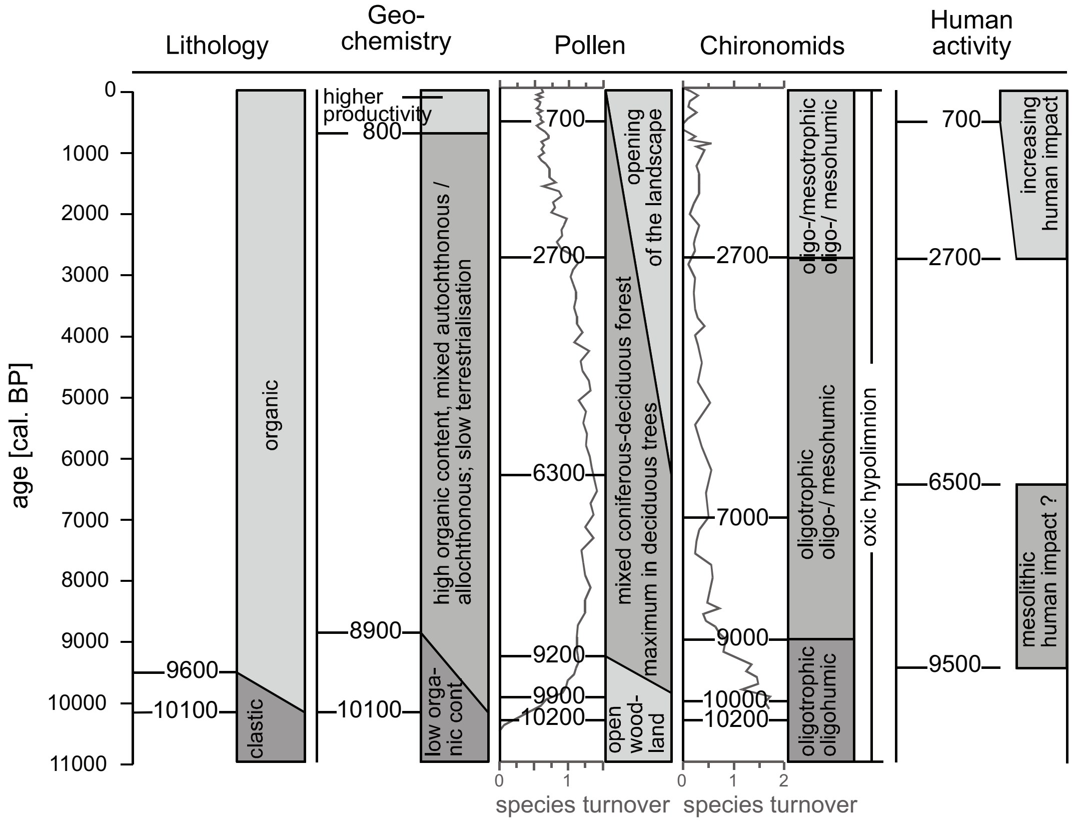


Figure 5.16: Summary of the ecological development of Reiarsdalsvatnet, reconstructed from the lithological description, geochemical, pollen, and chironomid analyses. Species turnover denotes sample scores of the first DCA axis [SD].

Initial phase (before 10,000 cal. BP)

The onset of the existence of chironomids in Reiarsdalsvatnet at 10,200 cal. BP is shown by the first finds of subfossil chironomid remains in low numbers (*Fig. 5.2*). This low total chironomid influx in the sample from 338 cm depth (10,180 cal. BP) is most likely due to poor food conditions, which is indicated by the low amount of organic matter in the sediment (*Fig. 4.9*). The presence of the ultraoligotrophic indicator *Heterotrissocladius subpilosus*-type together with *Micropsectra insignilobus*-type and *Stictochironomus* (*Fig. 5.1*) suggests a low productivity in the lake.

Transitional phase (10,000 cal. BP to 9,000 cal. BP)

Higher total influx of chironomid head-capsules indicates the establishment of the chironomid fauna in Reiarsdalsvatnet (*Fig. 5.2*). In addition, the increasing influx values point to growing lake productivity, which was also deduced from the pollen and geochemical data (Chapter 4). Thus increasing food availability was able to support a growing chironomid community. Characteristic during this phase is the abundance of *Microtendipes* before 9,000 cal. BP with maximum values at 9,700 cal. BP and decreasing values thereafter (*Fig. 5.1*). *Microtendipes* has been attributed to prefer relatively coarse sediments with low organic content (McGarrigle 1980) and its presence in the bottom of the core is probably due to the relatively low organic content in the sediment (*Fig. 4.15*) during this early phase.

Phase of stable conditions (9,000 cal. BP to 2,700 cal. BP)

The phase between 9,000 cal. BP and 2,700 cal. BP was very stable according to the chironomid assemblages, as shown by the stable species turnover (*Fig. 5.1*) and the PCA sample scores (*Fig. 5.11*). Trophic conditions of the lake are characterised by the dominance of oligotrophic taxa and by a stable but low influx of chironomid taxa characteristic of mesotrophic or eutrophic environments (*Fig. 5.4*). The abundance of *Heterotrissocladius marcidus*-type assigned to oligotrophic conditions (Boggero *et al.* 2006) together with a slightly increasing total influx of chironomid head-capsules (*Fig. 5.2*) and generally decreasing oligotrophic:eutrophic ratios (*Fig. 5.3*) support the assumption of oligotrophic conditions with a slowly increasing productivity at low levels. This assumption was also proposed in Chapter 4, based on the presence of macrophytes in the lake.

The increase of chironomid taxa characteristic of meso- to polyhumic conditions is the most distinct feature at the 9,000 cal. BP zone boundary (*Fig. 5.3*). The most important meso-/ polyhumic taxa in Reiarsdalsvatnet are *Heterotanytarsus apicalis*-type and *Heterotrissocladius marcidus*-type (*Fig. 5.1*). In addition, *Psectrocladius sordidellus*-type and *Ablabesmyia* are present (*Fig. 5.1*). These taxa have been found in dystrophic lakes in the Netherlands (Moller Pilot and Buskens 1990). Thus their presence supports the interpretation of increased humic content in Reiarsdalsvatnet after 9,000 cal. BP, even though both taxa are not listed in Sæther (1979) and therefore they are not included in the meso-/ polyhumic index.

Low productivity and the abundance of chironomid taxa indicating increased humic conditions might suggest dystrophic conditions for Reiarsdalsvatnet. Such a dystrophication process has been found in other North European lakes since the early Atlantic (cf. Brodin 1986). However, several indicators are contradictory to a severe dystrophication in Reiarsdalsvatnet. Dystrophic lakes receive large amounts of their organic matter from allochthonous sources in form of relatively resistant humic substances. This is expressed as a high organic colouring of the water, which leads to stable thermal summer stratification (Thienemann 1921, Wetzel 2001). The combination of low nutrient status and hypolimnetic oxygen depletion is characteristic of dystrophic lakes (Brundin 1949), and anoxic hypolimnia are frequent (Wetzel 2001). Due to this hypolimnetic oxygen deficit, *Chironomus* is characteristic of stratified dystrophic lakes (Brundin 1949).

In the case of Reiarsdalsvatnet, no severe oxygen depletion occurred in the profundal, as was demonstrated by the occurrence of low numbers of *Chironomus* (*Fig. 5.1*) together with low TS values in the sediment (*Fig. 4.10*). In addition, the presence of Isoëtes spp. (*Fig. 4.15*) contradicts a heavy colouring of the water (Scheffer 1998). Thus only a moderate increase in humic content took place in Reiarsdalsvatnet. This is supported by the sediment C:N ratios between 13 and 14 (*Fig. 4.10*), which suggest mesohumic conditions, since C:N ratios below 10 are typical for sediments from oligohumic lakes, while sediments from dystrophic lakes show C:N ratios greater than 10 to 15 (Hansen 1959). The importance of particulate organic matter in the water column as a food source for chironomids increased, as indicated by the onset of the presence of filter-feeders at 9,000 cal. BP.

With regard to the littoral area of Reiarsdalsvatnet, the slight increase in littoral taxa and the slight decrease of profundal taxa (*Fig. 5.2, 5.4*) suggest that the littoral area of the lake expanded slowly during this phase. This corresponds to the interpretation of C:S ratios and the presence of macrophytes presented in Chapter 4, where a slow terrestrialisation of the lake was proposed.

Phase of increasing productivity (2,700 cal. BP to present)

The relative decrease in chironomids characteristic of oligotrophic lakes and a slight increase in chironomids characteristic of eutrophic lakes indicate a slightly increasing lake productivity after 2,700 cal. BP (*Fig. 5.3*). This is supported by the highest values of total chironomid influx (*Fig. 5.2*), by an increase in *Ablabesmyia* and *Psectrocladius sordidellus*-type, both og which are reported from dystrophic to eutrophic lakes (Moller Pilot and Buskens 1990), by an increase in *Parakiefferiella bathophila*-type, reported from meso- to hypertrophic lakes (Moller Pilot and Buskens 1990), and by a decrease of *Heterotanytarsus apicalis*-type which is found in dystrophic to mesotrophic lakes (Moller Pilot and Buskens 1990). However, chironomids characteristic of oligotrophic conditions are dominant (*Fig. 5.3*), chironomids indicating eutrophic conditions are few (*Fig. 5.3*), and Isoëtes spp. are present in the lake (*Fig. 4.15*). Thus the nutrient status of the lake probably did not exceed mesotrophy.

After c. 1,000 cal. BP the highest total chironomid influx rates (*Fig. 5.2*) occur together with an increase in *Dicrotendipes*, which has been associated with meso- to hypertrophic and mesohumic conditions (Lotter *et al.* 1998, Moller Pilot and Buskens 1990, Sæther 1979), and in *Zalutschia zalutschicola*-type typically associated with oligotrophic and dystrophic conditions (Sæther 1979), (*Fig. 5.1*), suggest an increase in lake humic content. Nyman and Korhola (2005) found *Zalutschia zalutschicola*-type typical of large lakes with a high percentage of mires in their catchments. The growing importance of mires in the catchment of Reiarsdalsvatnet has already been shown by the maximum values of *Sphagnum* after 700 cal. BP (*Fig. 4.15*).

Isbenttjønn

Littoral chironomid taxa form the major part of the assemblages at Isbenttjønn, but a profundal chironomid fauna exists throughout the Holocene (*Fig. 5.7*). As in Reiarsdalsvatnet, the existence of a profundal chironomid fauna suggests that the lake becomes thermally stratified in summers (Stahl 1969). In contrast to Reiarsdalsvatnet, relatively high values of the profundal index are reached at Isbenttjønn. This is surprising since Isbenttjønn is more exposed to wind, due to the morphology of the catchment and the open birch forest around the lake. Thus thermal stratification should be less stable in Isbenttjønn than in Reiarsdalsvatnet. It cannot be finally decided whether the relatively high values of the profundal index are due to the bathymetry of the lake or if they may be an artefact of the dominant chironomid taxon *Sergentia*, which has not only been found in the profundal of temperate lakes but also in the littoral of high elevation lakes (Walker and Mathewes 1989).

According to *Sergentia* and *Micropsectra insignilobus*-type, both associated with oligo- to mesotrophic conditions (Sæther 1979, Wiederholm 1980), and according to the ecological indices, Isbenttjønn must be regarded as oligotrophic throughout the Holocene (*Fig. 5.7*). The presence of *Sergentia* and the absence of *Chironomus* indicate good to moderate oxygenated conditions in the hypolimnion throughout the Holocene. As stable influx of lotic chironomid taxa (*Fig. 5.6*) as well as stable influxes of Simuliidae, Ephemeroptera and Plecoptera (*Fig. 5.9*) after 8,800 cal. BP show, the inflow into Isbenttjønn remained stable during the Holocene. The latter three groups are all typical of running waters (Brittain and Saltveit 1996, Engblom 1996, Jensen 1997).

Initial phase (9,400 cal. BP to 8,800 cal. BP)

Total chironomid influx in Isbenttjønn shows the establishment of a chironomid fauna at the same time as the onset of organic matter accumulation in the sediment (9,300 cal. BP; *Fig. 4.10, 5.6*). Only very few head-capsules were found in the older sediment sample. A relatively high influx of chironomids during this initial phase (*Fig. 5.6*), together with the maximum in biogenic silica (*Fig. 4.16*) point to higher productivity of the lake compared to the period after 8,800 cal. BP. As discussed in Chapter 4, the nutrient availability during this phase was due to erosion from the catchment, where soil stability had not yet been reached. Still, high percentages of *Micropsectra insignilobus*-type and the presence of *Tanytarsus lugens* indicate that the nutrient status of the lake remained low (Sæther 1979), and oligotrophic conditions are also indicated by the ecological indices (*Fig. 5.7, 5.8*).

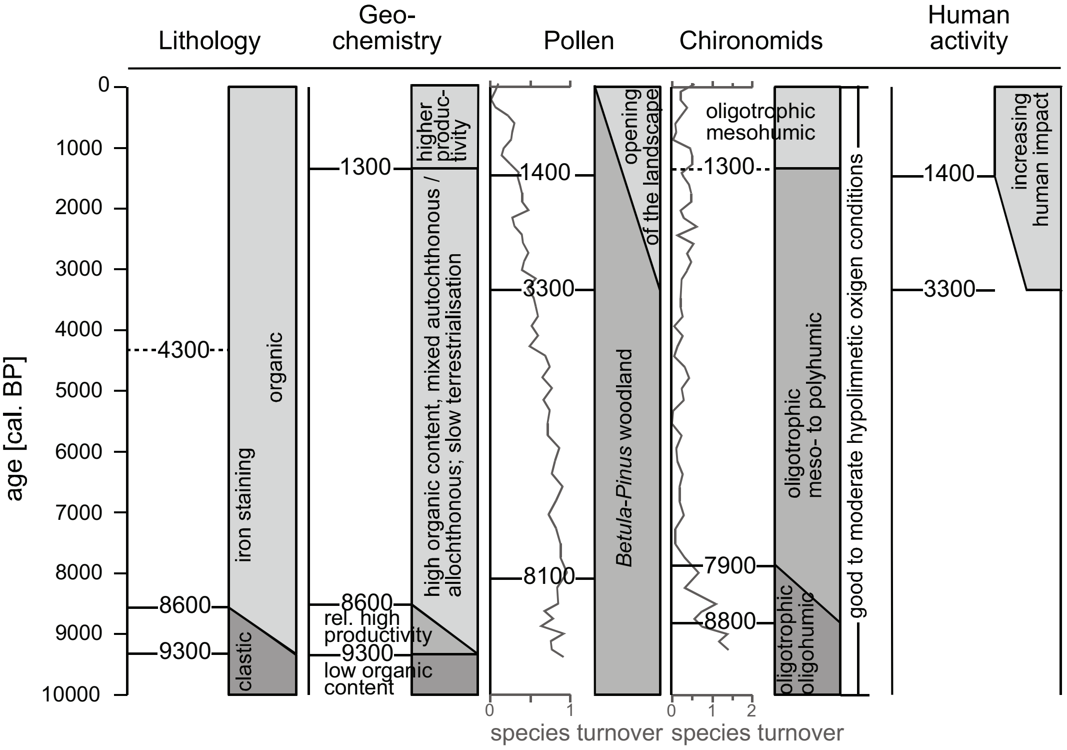


Figure 5.17: Summary of the ecological development of Isbenttjønn, reconstructed from the lithological description, geochemical, pollen, and chironomid analyses. Species turnover denote sample scores of the first DCA axis [SD].

During this phase, the ratio of littoral to profundal chironomids is very low (*Fig. 5.7*) suggesting that the profundal of Isbenttjønn was relatively large compared to the littoral. If this is an artefact caused by the fact that *Sergentia* is common in the profundal of temperate lakes, as well as beeing a littoral taxon in high elevation lakes (Walker and Mathewes 1989), or if it is due to a lower lake-level compared to the rest of the Holocene, cannot be decided from the available data. High TS contents together with the occurrence of vivianite iron staining of the sediment suggest oxygen depletion at the sediment-water interface during this phase (Chapter 4). However, chironomids indicate that anoxia did not pass over into the water-column, since *Micropsectra insignilobus*, which cannot withstand low oxygen conditions (Little *et al.* 2000), is dominant.

Transitional phase (8,800 cal. BP to 7,900 cal. BP)

During this phase, the influx of chironomids characteristic of profundal environments decreases (*Fig. 5.8*) and littoral taxa become more important (*Fig. 5.7*). This shift is mainly caused by the distinct decrease in *Micropsectra insignilobus*-type, which is characteristic of low nutrient status (Sæther 1979). The chironomid assemblage shows that Isbenttjønn was oligotrophic, with a slight increase of chironomids preferring eutrophic conditions at a low level (*Fig. 5.7*). The dominance of *Sergentia* together with the increase of chironomids indicating meso-/ polyhumic conditions (*Fig. 5.7*) and C:N ratios above 15 (*Fig. 4.16*), show an increase in humic content at Isbenttjønn. This is supported by the abundance of *Chaoborus flavicans* (*Fig. 5.9*), which is commonly found in dystrophic lakes. This species is able to migrate in the water column and can tolerate hypolimnetic oxygen depletion (Sæther 1997). As in Reiarsdalsvatnet, the growing importance of fine particulate organic matter in the water as food source for chironomids is indicated by the onset of the presence of filter-feeders (*Fig. 5.7*).

Phase of stable conditions (7,900 cal. BP to 1,300 cal. BP)

From 7,900 cal. BP to 1,300 cal. BP lake conditions indicated by the chironomid assemblages are stable as seen in the PCA analyses (*Fig. 5.13*). Total influx of chironomid head-capsules increases only slightly (*Fig. 5.6*) and the trophic index suggests that oligotrophic conditions prevailed in Isbenttjønn (*Fig. 5.7*). The increasing influx of chironomids characteristic of meso-/ polyhumic conditions with *Heterotrissocladius marcidus*-type being most important (*Fig. 5.7*), and the abundance of *Chaoborus flavicans* (*Fig. 5.9*) confirms a dystrophication process as it was deduced in Chapter 4 from the sediment C:N ratios above 15. This increase in humic content may have increased thermal summer stratification stability in the lake and decreased the phototrophic depth. Even though chironomids characteristic of littoral environments are dominant during this phase, a profundal chironomid fauna, with *Sergentia* and *Micropsectra insignilobus*-type as major taxa, persists in Isbenttjønn. The presence of the latter taxon and the low numbers of *Chironomus* show that good oxygenated conditions prevailed in the hypolimnion.

Phase of increasing productivity (1,300 cal. BP to present)

Even though the chironomid influx data (*Fig. 5.6*) and the profiles of the non-chironomid remains (*Fig. 5.9*) of Isbenttjønn show a distinct change at 1,300 cal. BP, no statistical significant chironomid assemblage zone could be detected from the percentage chironomid data. Thus the chironomid assemblages remained comparable to the ones before 1,300 cal. BP, only the influx increased considerably. *Sergentia* is the only taxon showing both decreasing influx and decreasing percentage values (*Fig. 5.6, 5.7*). The change at 1,300 cal. BP is also visible in the sample scores on the PCA axes 1 and 2 (*Fig. 5.12* and *Fig. 5.13*). While sample scores on both axes show parallel trends before 1,300 cal. BP, this is not the case after 1,300 cal. BP. During this youngest phase, PCA axis 1 values show a decreasing tendency while PCA axis 2 values increase distinctly. In addition, an increase in *Daphnia* abundance in the lake can be deduced from the increase in the numbers of daphnian resting eggs (ephippia) in the sediment (Jeppesen *et al.* 2003), (*Fig. 4.16*).

Daphnia are planktivorous zooplankton feeding on small algae and bacteria (Scheffer 1998), and they are known for their potential to graze algal biomass down to very low levels, which is responsible for the spring clear-water phase occurring in many shallow lakes (Scheffer 1998). The increase in *Daphnia* ephippia in Isbenttjønn after 1,300 cal. BP most likely mirrors an increase in food availability and thus an increase in primary productivity in the lake. Still, the trophic indicators show (*Fig. 5.7* and *Fig. 5.8*) that the influx of chironomids characteristic of oligotrophic conditions like e.g., *Heterotrissocladius marcidus*-type (Boggero *et al.* 2006) are most important, while the mesotrophic influx index increases only slightly at a low level and the eutrophic one remains almost constant. Thus even though an increase in productivity is indicated during the youngest phase, Isbenttjønn must still be regarded as oligotrophic.

No changes are detectable in the percentage index of chironomids characteristic of meso-/ polyhumic conditions (*Fig. 5.7*), but a slight decrease in C:N ratios to values below 15 (*Fig. 4.16*) indicates an increasing influx of autochthonous organic matter in comparison to the influx of allochthonous humic substances. In this context, attention should be paid to the decrease and disappearance of *Chaoborus flavicans* (*Fig. 5.9*). The main factor limiting the abundance of *Chaoborus* is the presence of planktivorous fish (Sweetman and Smol 2006). Since *Chaoborus flavicans* is able to migrate in the water column, it is less susceptible to predation pressure by fish than non-migratory *Chaoborus* species (Sweetman and Smol 2006). Thus the presence of *Chaoborus flavicans* in Isbenttjønn before 1,300 cal. BP and the absence of other *Chaoborus* species may be a sign of the presence of planktivorous fish. All *Chaoborus* species are most abundant in eutrophic and dystrophic conditions (Sæther 1997) due to food availability and the need for soft bottom sediments. A decrease of *Chaoborus flavicans* without a replacement by other *Chaoborus* species cannot be interpreted as a sign of decreasing predation by fish. In contrary, an increase in predation is possible, if the humic content in the lake decreases. This would cause less colouration of the water and thus the feeding pressure by visually feeding plaktivorous fish could have increased. This is more likely when taking into account that the presence and increasing influx of *Micropsectra insignilobus*-type indicates good hypolimnetic oxic conditions, which makes it possible for fish to catch prey not only in the epilimnion but also in the deeper waters of the lake. Thus the decrease in *Chaoborus flavicans* and the C:N values of the sediment suggest decreasing humic content after 1,300 cal. BP. Still, Isbenttjønn is regarded as mesohumic during this phase.

Another striking feature is the increase in the influx of Ceratopogonidae (*Fig. 5.9*). Since most aquatic ceratopogonid larvae inhabit shallow water (Szadziewski *et al.* 1997), their abundance might indicate a change in lake level. However, none of the other proxies indicates such a change. The chironomid littoral:profundal ratio (*Fig. 5.7*) does not change significantly compared to the rest of the profile, and the sediment proxies show only a minor change, which is interpreted as change in lake productivity (Chapter 4). The female ceratopogonid adults have fully functional biting mouthparts and need a blood-meal for egg-development, sucking blood from mammals, birds, frogs, and larger insects (Szadziewski *et al.* 1997). Thus the increase in Ceratopogonidae after 1,300 cal. BP possibly marks the beginning of pastoral activities in the vicinity of Isbenttjønn, with the regular presence of cows and sheep allowing for a larger Ceratopogonidae population. It is known that the huts (støls) at the lake shore (*Fig. 2.9*) have been used for the pasture of cows and goats for centuries (Chapter 2), and the presence of humans in the upper part of Setesdal during that time has as well been demonstrated by findings of places for charcoal and iron production. These have been dated to the period between 1,400 cal. BP and 580 cal. BP (Bloch-Nakkerud 1987, Martens 1988).

Sensitivity of the chironomid fauna to environmental changes

The non-significance of the results of the rate-of-change analyses for both pollen and chironomid data of both lakes (*Fig. 5.14, 5.15*) indicates that no abrupt changes occurred in the assemblages during the Holocene. The finding of sample scores distinctly below the 95 percentile of the permutation test is in line with the finding of Birks *et al.* (2000), who showed in a detailed Late Glacial sequence of Kråkeness, a lake situated in western Norway, that the rates-of-change of pollen and chironomids generally fell to consistent 'background' levels after the Younger Dryas.

Even though no abrupt changes occurred in Reiarsdalsvatnet and Isbenttjønn during the last c. 10,000 years, alteration processes in the lakes and in the catchments have been reconstructed in Chapter 4 and 5 of this study. The zonations of the proxies distinctly recognise different phases during the Holocene, but they do not indicate the cause of these changes. With regard to chironomids and pollen as proxies for the development of the lake and its catchment, the timing of the changes in the records may give closer insight to such triggers with the geochemical record of the lake sediments tying together allochthonous and autochthonous signals. Three generally different processes are possible in this context (cf. Lotter 2003):

a) A trigger (e.g. climate, human impact) causes changes in the vegetation and the lake system at the same time, i.e., it influences both the lake and its catchment directly. Because of the relatively long life-span of trees and the short life-cycle of chironomids, chironomids adapt faster to a changing climate, which should be seen earlier in the subfossil chironomid record than in the sediment pollen record. Since such biotic lags have been shown to be in the range of decades (Ammann 2000) they are not likely to be detected in the Reiarsdalsvatnet and Isbenttjønn records due to the temporal resolution between samples, which is 100 years and more (*Fig. 4.7, 4.8*). Thus in this case, changes should be seen by simultaneous changes in the different proxies.

b) A trigger (e.g. climate, human impact, soil development) causes changes in the vegetation, which alters the catchment, causes changes in the lake (e.g. nutrient status, oxygen status), and changes in the chironomid assemblages, i.e., the trigger influences the chironomid assemblages indirectly. This might be seen by lagged reactions in different proxies, depending on the rate of these processes.

c) A trigger (e.g. plant migration, lake ontogeny, lake acidification) independently changes the vegetation or the conditions in the lake. Thus changes in the pollen record would not be accompanied by changes in the lake-proxies and changes in the lake-proxies would not be paralleled by changes in the pollen record.

Reiarsdalsvatnet

The largest changes in all proxies are observed in the oldest part of the profile, indicated by multiple zones, each lasting only a few centuries (*Fig. 5.16*). The onset of a chironomid fauna in Reiarsdalsvatnet (10,200 cal. BP) coincides with the onset of organic sediment formation in the lake (10,100 cal. BP), which is mainly of autochthonous origin. This shows the direct relation between lake development, food availability, and chironomid presence in the lake. Parallel to this, the forest established rapidly around the lake, indicated by maximum tree pollen percentages at 9,900 cal. BP (*Fig. 4.11*). Since the period between 10,200 cal. BP and 9,900 cal. BP comprises only two samples in the pollen and the geochemistry record and three samples in the chironomid record, the changes in the different records are regarded as simultaneous. The same is true for the changes between 9,200 cal. BP and 8,900 cal. BP, comprising two samples in the geochemistry record and three samples in the pollen and the chironomid record. Thus the establishment of assemblages typical for the Holocene, as marked at 9,200 cal. BP for pollen, at 9,000 cal. BP for chironomids, and at 8,900 cal. BP in the geochemical data, are regarded as having occurred simultaneously.

With a zone boundary at 7,000 cal. BP, the chironomid record precedes the 6,300 cal. BP boundary in the pollen record (*Fig. 5.16*). No zone boundary is observed in the geochemical data during this phase. Here it is obvious from the timing that a direct influence of the vegetation in the catchment to the lake and thus to the chironomid assemblages did not occur. Thus the changes in both proxies can be either caused by the same process, with the pollen record showing the effects several centuries later than the chironomid record, or by different and independent triggers.

The zone boundary at 2,700 cal. BP is seen in the pollen and the chironomid record at the same time. The simultaneousness of the changes in both records suggests that one common trigger is responsible for the changes in the catchment and in the lake. This trigger may be beginning local human activity, since signs of this appear since 2,700 cal. BP in the pollen record (*Fig. 4.11*). However, the indicators of human impact suggest only moderate impact and changes in the lake cannot be deduced from the geochemical data (*Fig. 4.9*). Since the known transition from the Subboreal to the Subatlantic took place during this time, it is supposed that changes in climate were more influential than human impact during this phase.

The youngest zone boundaries are indicated at 800 cal. BP in the geochemistry data and at 700 cal. BP in the pollen record. They mark a further increase in local human activity, and signs for an increase in humic content and productivity are recognisable (*Fig. 5.16*). Still no zone boundary is apparent in the chironomid record, suggesting that these changes did not have a major impact on the chironomid assemblages.

Isbenttjønn

The onset of organic matter sedimentation at 9,300 cal. BP is indicated simultaneously in the lithology and the geochemical data (*Fig. 4.1, 4.10*), and is mirrored by the establishment of the chironomid fauna in Isbenttjønn after 9,300 cal. BP (*Fig. 5.17*). The pollen record shows that this change took place after the regional tree migration, and that no pollen zone boundary occurs at this time (*Fig. 5.17*). Thus the establishment of the chironomid fauna is closely related to the lake genesis and, like in Reiarsdalsvatnet, especially to food-availability. Such lake internal processes are most likely also responsible for the zone boundary at 8,800 cal. BP in the chironomid record, since no distinct changes are seen in the pollen stratigraphy during this phase.

Typical Holocene conditions are reached at 8,600 cal. BP according to the geochemical data (*Fig. 4.10*) and the lithology (*Fig. 4.1*). Typical assemblages are developed around 8,000 cal. BP in the pollen- and the chironomid records (*Fig. 4.11, 5.5*). The apparent age difference between the zone boundaries of both records (8,100 cal. BP vs. 7,900 cal. BP) is likely an artefact of the sample resolution (*Fig. 4.8*). Here, the geochemical zone boundary is clearly earlier than the zone boundaries in the biological proxies, suggesting that it does not record a linkage between changes in the catchment and in the lake in this case. The simultaneousness of the changes in the latter proxies suggests one common trigger, namely climate, to be responsible for the observed changes.

The pollen zone boundary at 3,300 cal. BP is not seen in any of the other proxy data (*Fig. 5.17*). Increasing charcoal influx might indicate early human impact, but if this is true, it did not affect the lake. A different picture can be seen around 1,350 cal. BP (*Fig. 5.17*). Zone boundaries are found for pollen at 1,400 cal. BP, for the geochemical record at 1,300 cal. BP, and for the chironomid record a minor one at 1,300 cal. BP. At that time, distinct changes occur also in the record of the non-chironomid remains. The general simultaneousness of the changes suggests the same process to have triggered those changes either directly or indirectly. The slight precedence of the pollen record compared to the other proxies indicates that the changes in the chironomid assemblages may have been mediated by changes in the vegetation. Thus changes in climate or human impact triggered changes in the catchment directly, but may have triggered changes in the lake indirectly.

Conclusions

The palaeoecological development of Reiarsdalsvatnet and Isbenttjønn has been reconstructed based on the qualitative interpretation of the analyses of subfossil chironomid remains against the background of the pollen and geochemical data presented in Chapter 4. The main conclusions are the following (cf. *Fig. 5.16, 5.17*):

1. Thermal stratification and hypolimnetic oxygen conditions: In both Reiarsdalsvatnet and Isbenttjønn, a profundal chironomid fauna exists. Both lakes are expected to develop thermal stratification during summers, but due to their moderate depths, the stratification is not likely to be very stable. The chironomids indicate well oxygenated conditions in the hypolimnion of Reiarsdalsvatnet and good to moderate hypolimnetic oxygen conditions for Isbenttjønn during the Holocene.
2. Trophic status: Both lakes are regarded as oligotrophic according to the chironomid record. However, they experience increasing productivity at low levels, indicated in the younger sediments. Reiarsdalsvatnet reaches oligo- to mesotrophic conditions, but Isbenttjønn does not exceed an oligotrophic state.
3. Humic status: The influx of allochthonous humic substances is an important source of organic matter in both lakes. Reiarsdalsvatnet is regarded as oligo- to mesohumic, while Isbenttjønn shows a development from oligohumic to meso-/ polyhumic and back to oligo-/ mesohumic conditions, according to the chironomid record and the geochemical data.
4. Stability of lake conditions: No abrupt changes during the last c. 9,500 years were detected in any of the lakes, as shown by the rate-of-change analyses.

According to the comparison of the timing of changes in the different proxies, no signs of a direct dependence of the chironomid assemblages to the catchment vegetation in the catchments were found. This supports Seppä *et al.* (2002), who found ‘not much evidence for a direct relationship between chironomid assemblages and the inferred tree-line position per se’. However, Heiri *et al.* (2003c) state that chironomid-inferred climate signals that parallel distinct changes in sediment composition should certainly be treated with caution. Thus attention should be paid to the following periods when inferring temperatures based on chironomids:

- Reiarsdalsvatnet (*Fig. 5.16*): Changes in the proxies occurred simultaneously around 10,000 cal. BP due to catchment and lake instability and around 9,000 cal. BP, when stable Holocene conditions were reached. At 2,700 cal. BP another simultaneous boundary is marked in the chironomid and pollen records, but it is not visible in the geochemical data. This boundary is suggested to be caused by changes in climate.
- Isbenttjønn: The zone boundary in the chironomid record at 8,800 cal. BP is not paralleled by changes in the pollen data and is thus most likely due to lake internal processes connected to lake genesis. After 8,600 cal. BP (geochemical data) and 8,000 cal. BP (biological proxies), typical Holocene conditions are reached. The simultaneousness of the changes in the biological proxies suggest climate to be responsible for these changes. Changes in all proxies are seen around 1,350 cal. BP, where the boundary in the pollen record precedes the one in the geochemical record and in the chironomid influx data slightly. Here, changes in the chironomid assemblages may have been mediated by changes in the vegetation, both triggered by either climate or human impact.

With regard to the initial questions, the chironomid records support the assumption from Chapter 4 that both lakes and their catchments have undergone only minor changes during the Holocene. Thus it is proposed that these sites are suitable for chironomid-based quantitative summer temperature reconstructions.

Chapter 6: Reconstruction and evaluation of Holocene mean July temperatures

Introduction

Quantitative temperature reconstructions based on subfossil chironomids have been shown to record century-scale summer temperature changes well, when compared to meteorological data (Larocque and Hall 2003). However, distinct differences have been found in the Holocene chironomid-inferred temperature records when comparing chironomid-inferred temperatures from several sites in one region (e.g. Rosén *et al.* 2003, Rosenberg *et al.* 2004, Velle *et al.* 2005a), or when comparing chironomid-inferred temperatures with quantitative reconstructions based on other biological proxies from the same site (e.g. Bigler *et al.* 2002, Larocque 2004, Rosén *et al.* 2001). As stated in Chapter 1, these differences are assumed to be due to local influences on the lake and hence on its chironomid assemblages. The influence of such local factors is supposed to be large because most of the studied sites cited above are located close to the alpine or the arctic tree-line. This makes the lakes especially sensitive to environmental changes (Lotter *et al.* 1999), including not only changes in broad-scale factors (e.g., climate), but also changes in local scale factors (e.g., soil development). To minimise these local factors, in this study sites located well below the modern tree-line with stable environmental conditions during the Holocene were chosen for chironomid-based temperature reconstructions.

The aim of this Chapter is to assess if chironomids from such lakes record small-scale Holocene temperature variations and to what extent chironomid-based temperature reconstructions are influenced by factors other than climate. A special emphasis is given to human impact. The results are compared to previously published records of chironomid-inferred mean July temperatures from alpine or arctic sites. To allow for this comparison, the isostatic uplift of the study sites is taken into account since it has locally different impacts on palaeotemperatures.

The palaeoecological development of the south Norwegian lakes Reiarsdalsvatnet (245 m asl) and Isbenttjønn (787 m asl) has been characterised in Chapters 4 and 5. It has been shown that the conditions in both lakes have been relatively stable throughout the Holocene and that no major or abrupt changes occurred in the lakes during the studied period. Thus they are regarded as suitable sites for the assessment of the question if non-alpine sites are appropriate for chironomid-based quantitative temperature reconstructions of small-scale summer temperature variations.

In this Chapter, quantitative chironomid-inferred mean July temperatures are presented together with pollen-inferred mean July temperatures from the same sites, both reconstructed using weighted averaging partial least squares regression (WA-PLS), (ter Braak and Juggins 1993). Taking the palaeoecological development of the lakes and their catchments as reconstructed in Chapter 4 and Chapter 5 into account, the reliability of the chironomid-inferred temperatures is evaluated by the following three different approaches (cf. Birks 1995, 2003, Imbrie and Webb 1981):

- The statistical reliability of the chironomid- and the pollen-based temperature reconstructions is evaluated using different numerical criteria.
- The chironomid-inferred temperatures are validated with the independent pollen-inferred temperatures from the same sediment samples.
- The temperature reconstructions of both lakes are validated by comparisons with previously published and independent palaeoclimate records.

Results

Chironomid- and pollen-inferred mean July temperatures

Before reconstructing mean July temperatures, samples with less than 50 chironomid head-capsules were omitted from the chironomid-records because temperature reconstructions based on such low count sums have been shown to be unreliable (Heiri and Lotter 2001, Larocque 2001, Quinlan and Smol 2001). In total, three samples were excluded from the Reiarsdalsvatnet record, and four from the Isbenttjønn record (*Fig. 6.1, 6.2*, *Tab. A3*).

In considering the reconstructed temperatures, it should be taken into account that reconstructions of very low and very high temperatures, i.e., temperatures at the end of the gradients of the modern calibration data, are less reliable than the reconstruction of middle-range temperatures. This is due to the ‘edge-effect’ inherent in all weighted average-based models (Birks 2003), and results in an over-estimation of low values and an underestimation of high values (ter Braak and Juggins 1993). From the Norwegian pollen calibration data-set it can be deduced that the reconstruction of temperatures below c. 11°C generally yields values that are too high (cf. Seppä and Birks 2001, H.J.B. Birks and S.M. Peglar, unpublished data). This distinct bias is not only due to inherent edge-effects in WA-PLS but most likely also due to the influence of long-distance transported pollen from the lowlands (Seppä and Birks 2001). In the Norwegian chironomid calibration data-set no distinct bias is present at the lower end of the temperature gradient (c. 3.5°C), (cf. Brooks and Birks 2001, S.J. Brooks and H.J.B. Birks, unpublished data). The upper end of the temperature gradient is located at c. 16°C for both proxy data-sets and a bias towards too low reconstructed temperatures is obvious at temperatures above c. 14.5°C (cf. Brooks and Birks 2001, Seppä and Birks 2001, H.J.B. Birks and S.M. Peglar, unpublished data, S.J. Brooks and H.J.B. Birks, unpublished data).

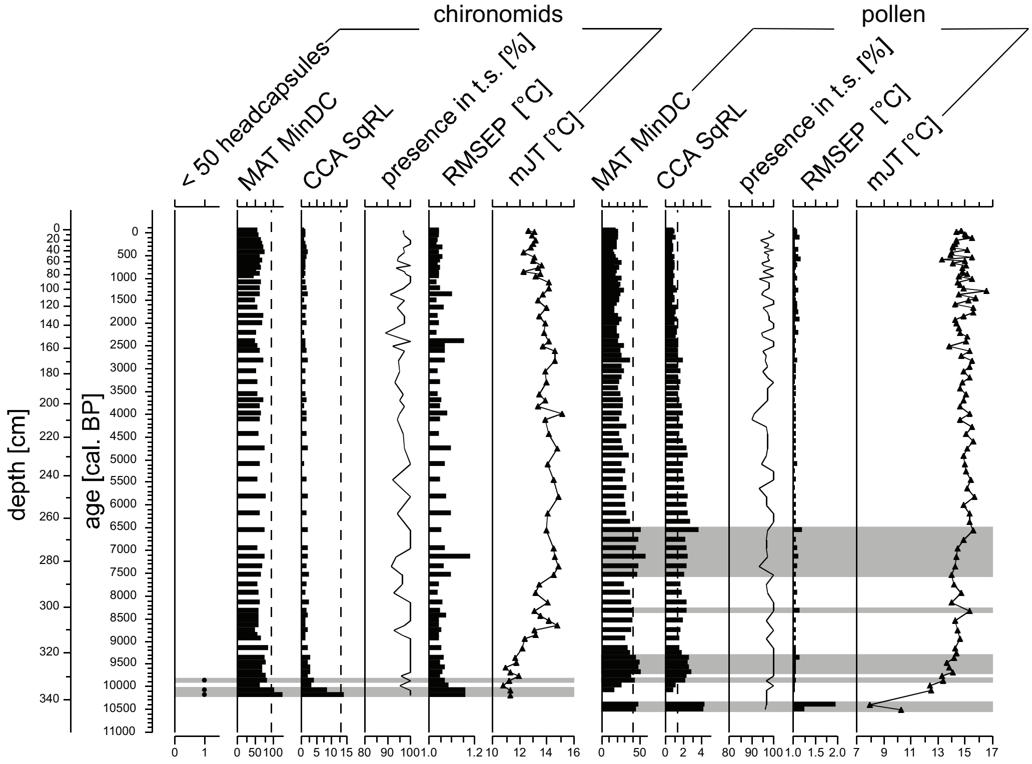


Figure 6.1: Summary of the sample specific numerical evaluation criteria values for Reiarsdalsvatnet. Areas shaded in grey mark samples omitted from the records of chironomid- and pollen-based temperature reconstructions. MAT MinDC: minimal chi-square distance to the closest modern analogue, CCA SqRl: squared residual distance to the first CCA axis, and 'presence in t.s.': representation of subfossil taxa in the modern training-set (cf., Chapter 3). Dashed lines indicate significance levels.

Reiarsdalsvatnet

Holocene chironomid- and pollen-based mean July temperature reconstructions from Reiarsdalsvatnet show a similar behaviour when looking at centennial to millennial-scale fluctuations (*Fig. 6.3*). Three main trends are distinct: increasing temperatures before c. 7,000 cal. BP, slowly decreasing temperatures between c. 7,000 cal. BP and c. 1,500 cal. BP and more rapidly decreasing temperatures after c. 1,500 cal. BP (*Fig. 6.3*). Temperatures reach their Holocene mean by 8,700 cal. BP (13.5°C for chironomid-, 14.6°C for pollen-inferred temperatures). Maximum Holocene temperatures are recognised at c. 7,200 cal. BP (chironomids: 14.6°C) and c. 6,100 cal. BP (pollen: 15.3°C), (*Fig. 6.3*), respectively, where the inferred temperatures are 0.3 K to 1 K higher than the estimated present-day temperature. A short period of lower temperatures occurs around 3,500 cal. BP. Temperatures are again on a level comparable to the Holocene maximum around 2,800 cal. BP, whereas a local minimum appears at c. 2,100 cal. BP (pollen) and c. 1,700 cal. BP (chironomids). The following local maximum around 1,300 cal. BP is distinctly higher in the pollen-inferred temperatures (15.2°C) than in the chironomid-inferred ones (14°C). After

1,000 cal. BP the chironomid-inferred temperatures drop slightly earlier than the pollen-inferred ones, but both reconstructions are very similar during this youngest period. The main differences in the reconstructions occur between c. 7,900 cal. BP and c. 6,500 cal. BP, when chironomid-inferred temperatures show a local maximum while a local minimum can be seen in the pollen-inferred temperatures (*Fig. 6.3*), and the generally lower chironomid-inferred temperatures compared to the pollen-inferred ones (difference in mean Holocene temperatures: 1.1°K).

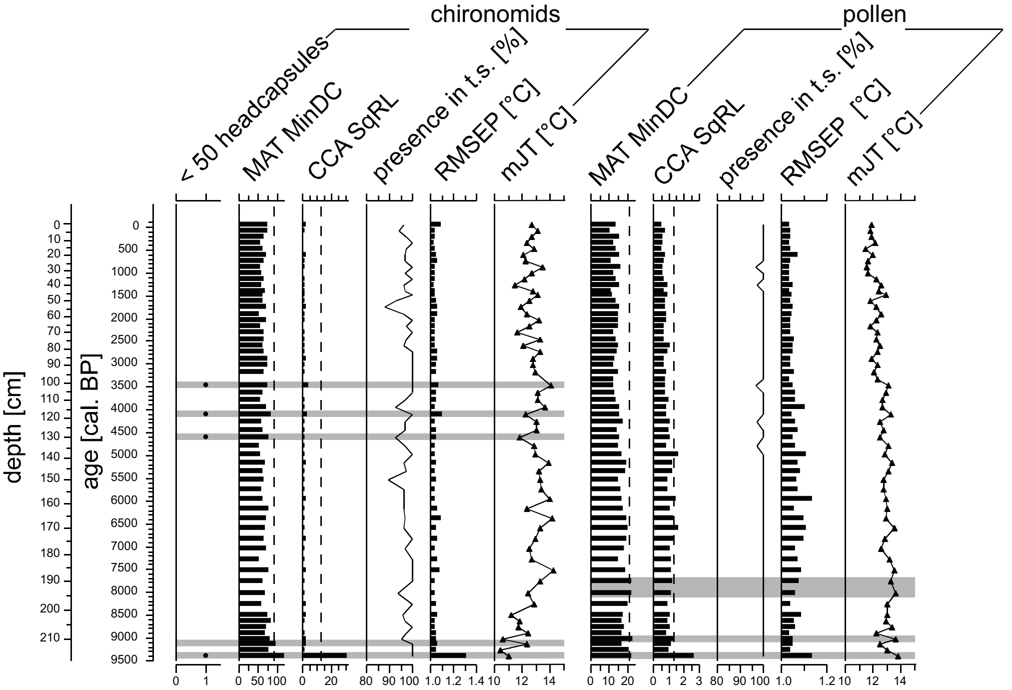


Figure 6.2: Summary of the sample specific numerical evaluation criteria values for Isbenttjønn. Areas shaded in grey mark samples omitted from the records of chironomid- and pollen-based temperature reconstructions. MAT MinDC: minimal chi-square distance to the closest modern analogue, CCA SqRl: squared residual distance to the first CCA axis, and 'presence in t.s.': representation of subfossil taxa in the modern training-set (cf., Chapter 3). Dashed lines indicate significance levels.

The sample-specific prediction error estimates (RMSEP) have shown values of 1.06°C for chironomid- and 1.10°C for pollen-inferred temperatures (*Fig. 6.1*). The maximum RMSEPs are 1.18°C (chironomids) and 1.97°C (pollen), and minimum values are 1.04°C for both reconstructions. The relative sea-level at Reiarsdalsvatnet over the studied period of the Holocene, as modelled with the software 'SeaLevel Change' (Møller and Holmeslet 1998), did not change more than 20 m compared to today's shoreline. Thus the influence of isostatic uplift on the temperature can be disregarded.

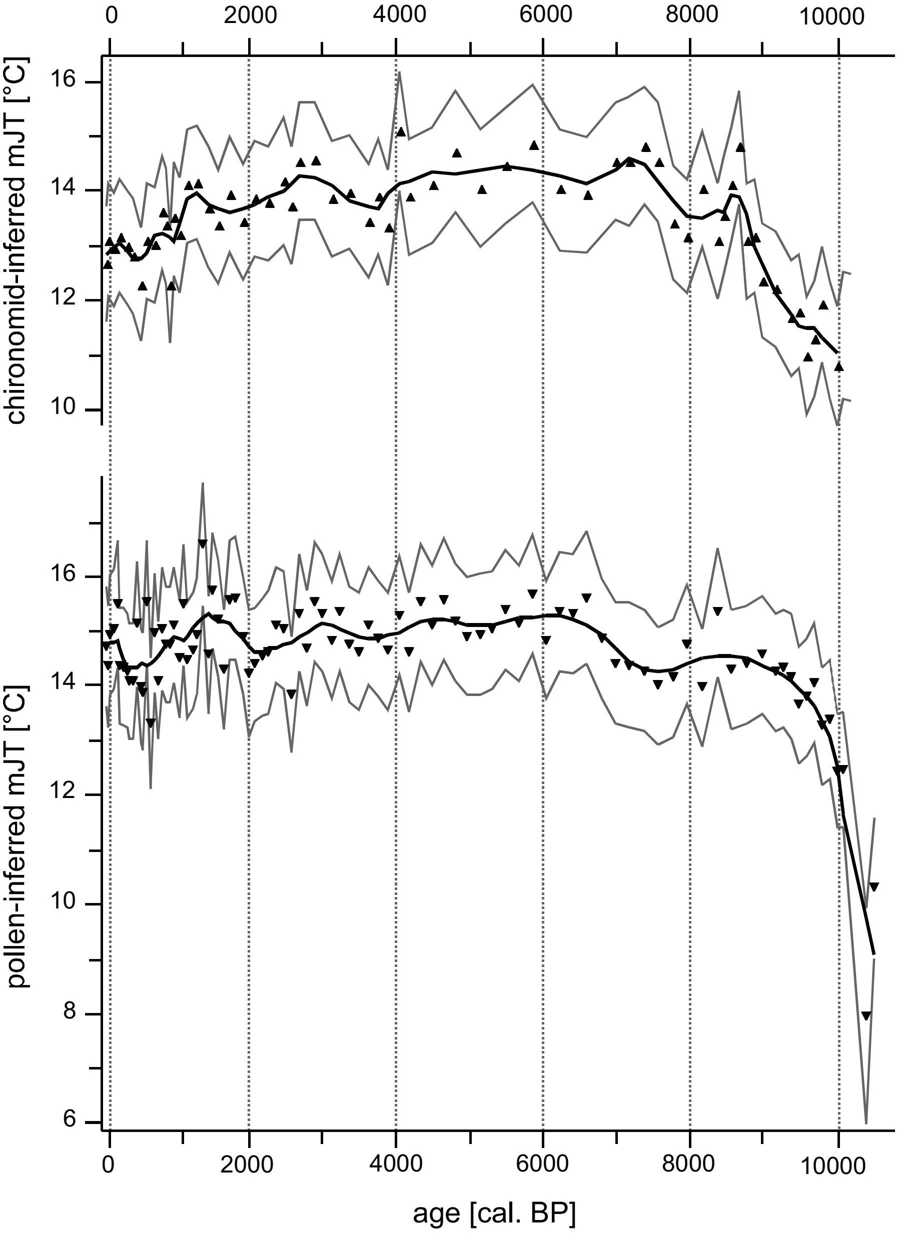


Figure 6.3: Chironomid- and pollen-inferred mean July temperatures (mJT) for Reiarsdalsvatnet. The reconstructed temperatures for each sample are shown as triangles, the sample specific error estimates as thin grey lines. Century-scale temperature trends are highlighted by a LOWESS smoother (bold line).

Isbenttjønn

For the Isbenttjønn record, the chironomid- and the pollen-inferred temperature reconstructions (*Fig. 6.4*) both have a Holocene mean of 12.7°C. The general Holocene temperature trends seen in both reconstructions are increasing temperatures between 9,000 cal. BP and 7,600 cal. BP, constant to slightly decreasing temperatures from 7,600 cal. BP to 3,600 cal. BP, and a more rapid decrease in temperatures from 3,600 cal. BP to 1,300 cal. BP (*Fig. 6.4*). Between 9,000 cal. BP and 1,300 cal. BP both temperature reconstructions are very similar especially when regarding the variations on a centennial to millennial-scale (*Fig. 6.4*). Both records reach Holocene maximum mean July temperatures of 13.5°C around 7,600 cal. BP, disregarding the oldest sample

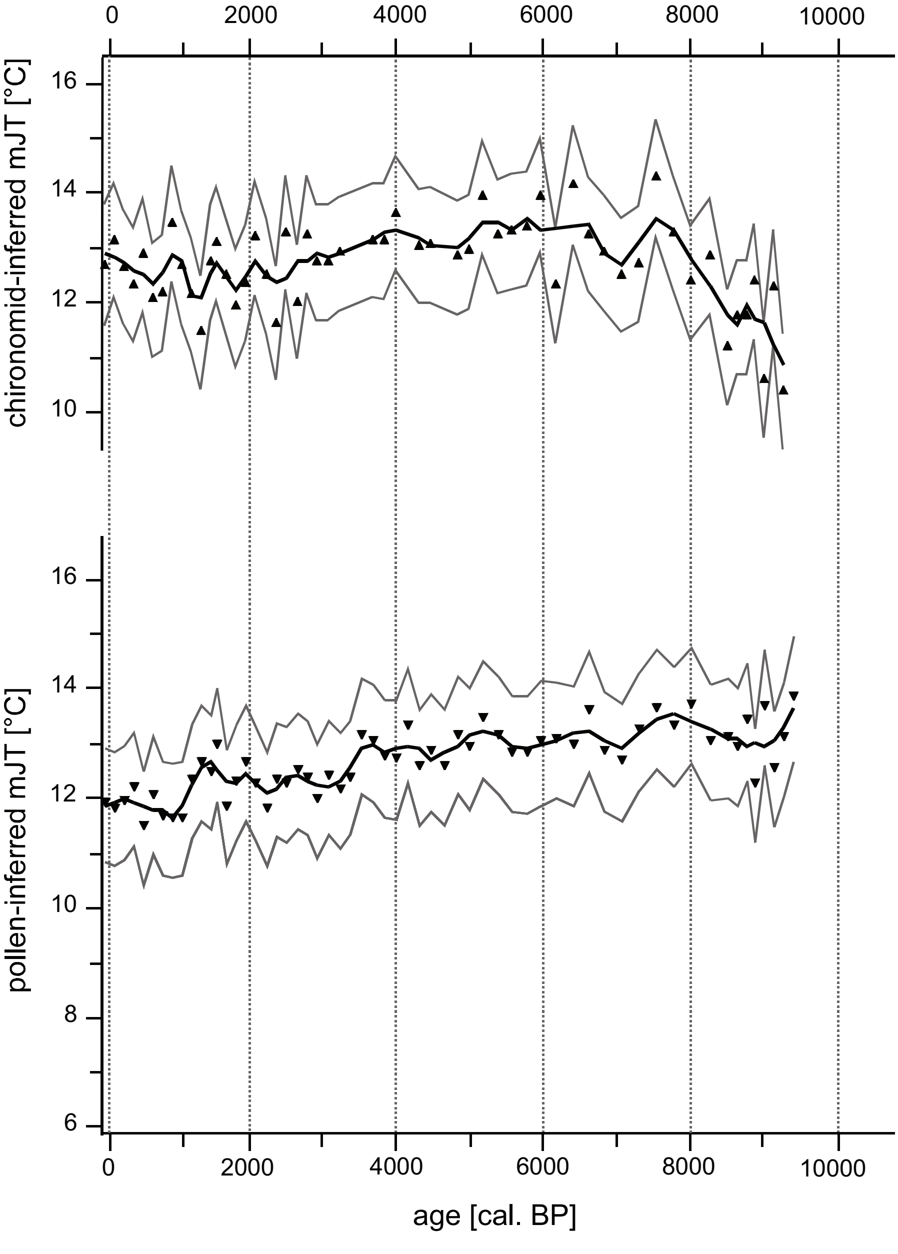


Figure 6.4: Chironomid- and pollen-inferred mean July temperatures (mJT) for Isbenttjønn. The reconstructed temperatures for each sample are shown as triangles, the sample specific error estimates as thin grey lines. Century-scale temperature trends are highlighted by a LOWESS smoother (bold line).

in the pollen record. This inferred maximum temperature is 3.5 K higher than the modelled present-day temperature. Two periods of lower temperatures are recognisable, a distinct one between 7,600 cal. BP and 6,600 cal. BP and a less distinct one between 5,200 cal. BP and 4,000 cal. BP (*Fig. 6.4*). Obvious differences between both temperature reconstructions occur before 9,000 cal. BP, where pollen-based reconstructions show high temperatures compared to the chironomid-inferred ones. A second period of temperature differences occurs after 1,300 cal. BP, where chironomid-inferred temperatures are distinctly higher than pollen-based reconstructions.

Mean sample-specific RMSEPs are 1.05°C for the chironomid-based reconstructions and 1.06°C for the pollen-based ones (*Fig. 6.2*). Maximum values reach 1.10°C (chironomids) and 1.14°C (pollen) and minimum values are 1.03°C for both reconstructions. The relative sea-level was c. 60 m higher at c. 9,400 cal. BP than today in the region around Isbenttjønn (cf. Møller and Holmeslet 1998). The strongest gradient of relative sea-level change in the analysed interval of the Holocene occurred between 9,400 cal. BP and c. 8,900 cal. BP, where the relative sea-level dropped from c. 60 m to 45 m. Thereafter, it decreased linearly to today's shoreline. When taking the lapse rate of 0.57 K per 100 m altitude into account, the temperatures have been 0.34 K lower than reconstructed in the oldest part and less than 0.23 K lower than reconstructed after 8,900 cal. BP, both due to isostatic uplift. Since these values are small compared to the long-term changes in the reconstructed temperatures, the effect of isostatic uplift can be disregarded for the Isbenttjønn record.

Numerical evaluation criteria

Modern analogues, 'goodness-of-fit' statistics, sample specific RMSEPs, and the percentage of taxa in each sample that are present in the modern calibration data were determined to estimate the goodness of the chironomid- and pollen-inferred temperatures (*Fig. 6.1, 6.2*). Less reliable temperature reconstructions were determined by regarding the sample-specific results of all numerical criteria jointly, following a conservative approach categorising as few samples as possible as unreliable. The latter is due to the fact that less reliable temperature reconstructions cannot be regarded as wrong and their exclusion would lead to a distinct loss of information. In total, the temperature reconstructions of 14 samples from the Reiarsdalsvatnet pollen-record, one sample from the Isbenttjønn chironomid-record and four samples of the Isbenttjønn pollen-record were categorised as 'less reliable' due to these criteria (*Fig. 6.1, 6.2, Tab. A3*). In addition, one temperature reconstruction from the Reiarsdalsvatnet pollen-inferred temperature record is statistically unreliable (1,280 cal. BP, 16.6°C), since it exceeds the temperature range of the modern calibration data-set. These 'less reliable' samples were not excluded from the record, but they were marked in the final graphs.

From the results it is obvious that a cut-level of a distance to the closest modern analogue (MinDC) larger than the extreme 10 % of the modern calibration data generally is a good value to distinguish samples that differ in reliability from the rest of the profile (*Fig. 6.1, 6.2*). Only for the pollen record from Reiarsdalsvatnet this cut-level is too low. With a cut-level of 10, about two thirds of the samples would be categorised as ‘less reliable’, though the sample-specific RMSEPs for these samples are not particularly high and the percentage of fossil taxa present in the modern calibration data mostly exceeds 95 %. According to the joint consideration of all criteria, a cut-level of MinDCs of 40 is regarded to represent less reliable temperature reconstructions in the pollen record from Reiarsdalsvatnet. These samples with a MinDC larger than 40 also show a large squared residual distance from the first CCA axis (CCA SqRL) and many of them show relatively high RMSEPs (*Fig. 6.1*).

Interpretation and discussion

Palaeoecological consideration of the ’less reliable’ temperature reconstructions

Quantitative palaeoenvironmental reconstruction procedures always produce results. Thus the goodness of the inferred temperatures needs to be evaluated, even though such an evaluation has received surprisingly little attention so far (Birks and Birks 2003). Several numerical evaluation criteria have been proposed for the estimation of the reliability of quantitative reconstructions (Birks and Birks 2003, Birks 1998), but there is no strict evaluation procedure. Thus, different numerical criteria or a combination of criteria have been proposed and used in palaeoclimatological studies (e.g. Bigler *et al.* 2002, Birks 1998, Birks *et al.* 1990, Hammarlund *et al.* 2004, Heiri *et al.* 2003b, Larocque and Hall 2004, Velle *et al.* 2005a). In addition, different cut-levels have been proposed for the determination of less reliable reconstructions in these studies, but it must be taken into account that the fixing of cut-levels is an *ad hoc* approach and not a rigorous statistical measure.

All of the numerical criteria attempt to estimate how much the fossil assemblages differ from the assemblages in the modern calibration data, supposing that a reconstructed temperature is more reliable if it is based on a fossil assemblage that is well represented in the modern calibration data-set. Samples with high modern analogue values, high values for the ‘goodness-of-fit’ statistics, high sample specific RMSEPs, or low percentages of taxa present in the modern calibration data may point to phases in the palaeoecological history where different processes may have taken place compared to the rest of the profile. Some of these differences can be explained by taking into account the palaeoecological reconstructions (Chapter 4 and 5).

Reiarsdalsvatnet

Only samples with low count sums were omitted from the chironomid-based reconstructions in Reiarsdalsvatnet, and all of them are older than 9,800 cal. BP (*Tab. A3*). The low number of head-capsules is due to low head-capsule influx

(*Fig. 5.2*). This is explained by low organic content in the sediment indicating poor food conditions for chironomids (cf., Chapter 4).

With regard to the pollen record, three main phases of 'less reliable' temperature reconstructions have been detected: before c. 10,200 cal. BP, from 9,900 cal. BP to 9,300 cal. BP, and from 7,600 cal. BP to 6,500 cal. BP (*Fig. 6.1*). Generally, the high values in the numerical evaluation criteria for the Reiarsdalsvatnet pollen record (*Fig. 6.1*) are due to the high percentages of *Corylus*, which does not exceed 5 % in any of the surface samples in the modern calibration data (H.J.B. Birks and S.M. Peglar, unpublished data). This role of *Corylus* becomes obvious in the similarity of the percentage record of *Corylus* (*Fig. 4.11*) and the MinDC record (*Fig. 6.1*).

The samples older than 10,200 cal. BP constitute RVpz 1 (*Fig. 4.11*). The reconstructed temperatures are at the lower end of the calibration curve, where the WA-PLS model generally produces too high temperatures due to the 'edge effect' and to the influence of long-distance transported pollen, as explained above (Seppä and Birks 2001). In addition, these temperature reconstructions are based on relatively low count sums of less than 400 pollen grains, which adds to the statistical uncertainty of the reconstructed temperatures and is partly responsible for the high values in the numerical evaluation criteria. The maximum MinDC values between 9,900 cal. BP and 9,300 cal. BP and between 7,600 cal. BP and 6,500 cal. BP correspond to the high *Corylus* percentages (*Fig. 4.11, 6.1*). During the latter period, the main differences between the chironomid- and the pollen-inferred temperatures have been observed (*Fig. 6.3*). The combination of differences in the reconstructed temperatures and the fact that the pollen-inferred temperatures are less reliable during this period, leads to the assumption that here the chironomid-inferred temperatures may come closer to the true temperature fluctuations than the pollen-inferred ones.

Isbenttjønn

From the Isbenttjønn chironomid record, four samples were omitted, because of low count sums (*Fig. 6.2, Tab. A3*). The head-capsule influx rate of the oldest of these samples (9,400 cal. BP) is very low (*Fig. 5.6*), which is, as in Reiarsdalsvatnet, due to low lake productivity and the low organic content in the sediment (*Fig. 4.10*). Thus poor food conditions caused the low head-capsule influx. The low head-capsule sum of the younger three samples (4,600 cal. BP, 4,100 cal. BP, 3,600 cal. BP) is due to problems in the chironomid preparation procedure (too little material available) and is thus not connected to particular palaeoecological conditions. One sample is rejected from the temperature reconstruction because of a high MinDC value (9,100 cal. BP; *Fig. 6.2*). This is due to high percentages of the taxon Tanytarsus 'no spur' (*Fig. 5.5*). Such high percentages do not occur in the modern calibration data (S.J. Brooks and H.J.B. Birks, unpublished data). Since in this taxon critical characteristics allowing the identification to species-type are absent, the high percentage is most likely an indication of bad preservation conditions in the sediments compared to the rest of the profile. This is also documented by the high percentages of unidentified Pentaneurini (*Fig. 5.5*). A negative peak in TOC and a slight increase in dry density at the same time (*Fig. 4.9*) suggest higher percentages of clastic material in the sediment, which might have caused the poor preservation of head-capsules.

With regard to the pollen-inferred temperatures, all four samples with 'less reliable' temperature reconstructions cannot clearly be assigned to single peaks in the pollen record, but all samples have maximum values in species turnover (*Fig. 4.13*). The two older samples are part of ITpz 1 (9,400 cal. BP and 9,000 cal. BP; *Fig. 4.13, 6.2*). As in the Reiarsdalsvatnet record, these samples are characterised by maximum percentages of *Corylus*, even though the values in Isbenttjønn do not reach 10 %. The younger two samples with 'less reliable' temperature reconstructions date from 8,000 cal. BP and 7,800 cal. BP (*Fig. 6.2*), which is the onset of ITpz 2 (*Fig. 4.13*). However, no explanation for this lack of close modern analogues can be deduced from the palaeoecological reconstructions.

With regard to the differences between the chironomid- and the pollen-inferred temperatures in Isbenttjønn, only the phase before 9,000 cal. BP can be assigned to statistical causes. The distinct differences after 1,300 cal. BP are not connected to reliability problems in the reconstructed temperatures as inferred from the numerical evaluation criteria.

Site-specific validation of the chironomid-inferred temperatures

The only possibility to evaluate the chironomid-inferred temperatures directly is by point-wise comparison to the independent pollen-inferred temperatures from the same profile. To allow for this comparison, only temperature reconstruction based on both chironomids and pollen derived from the same samples are included (*Fig. 6.5, 6.6*).

Reiarsdalsvatnet

In the Reiarsdalsvatnet profile, the point-wise comparison of the chironomid-inferred and the pollen-inferred mean July temperatures, shows a significant correlation (Spearman rank correlation coefficient: $r = 0.49$, $p < 0.01$; *Fig. 6.5*). The strength of the correlation increases when samples with temperature reconstructions categorised as 'less reliable' based on the numerical evaluation criteria (*Fig. 6.1*) are excluded ($r = 0.53$, $p < 0.01$). Thus the chironomid-inferred temperatures resemble the independent pollen-inferred temperatures very well. The main difference is that the chironomid-inferred temperatures are generally lower. This fact cannot easily be explained. Only a few studies have been conducted that infer temperatures quantitatively based on chironomids and pollen using WA-PLS regression for the same core. These are for the Late Glacial the study from Kråkenes (Birks *et al.* 2000, Brooks and Birks 2000), and for the Holocene the studies from northern Sweden: Vuoskkujávi (Bigler *et al.* 2002), Seukokjaure (Rosén *et al.* 2003), and Sjuodjijaure (Rosén *et al.* 2003, Rosén *et al.* 2001). These records do not give a uniform picture of one of the proxies resulting in higher temperatures than the other. In addition, the reconstructed temperatures in these studies are all, apart from single values, lower than 12°C and thus may not be directly comparable to the record of Reiarsdalsvatnet.

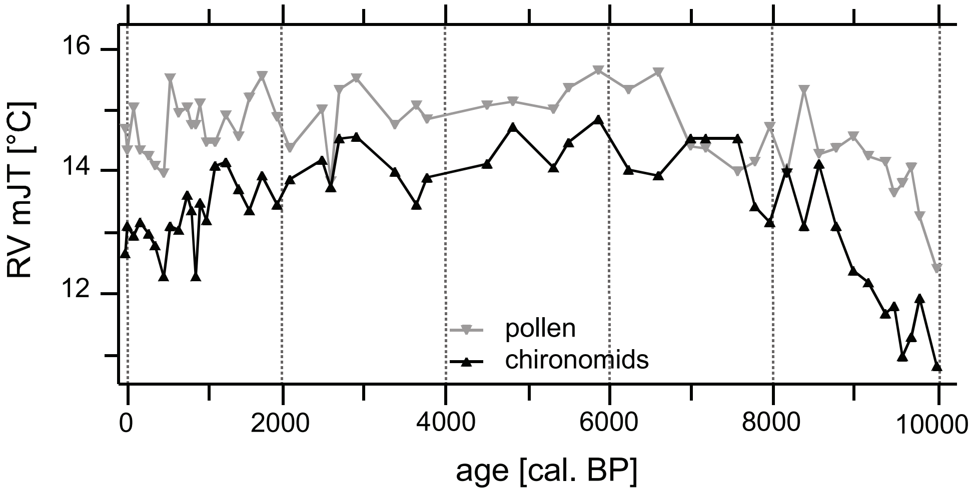


Figure 6.5: Chironomid- and pollen- inferred mean July temperatures for selected samples of Reiarsdalsvatnet. To enable a point-wise comparison of the temperatures, only samples with available chironomid- and pollen-inferred temperatures are shown.

To assess if the general level of the chironomid-inferred or the pollen-inferred temperatures is more plausible, some comparisons with known temperatures and temperature gradients can be done. Regarding the surface sample of the core, the pollen-inferred 14.7°C is closer to the modelled temperature of 14.3°C from the modern calibration data, than the chironomid-inferred 12.7°C is. In addition, assuming the mean Holocene temperature for Isbenttjønn of 12.7°C as reliable, and extrapolating the temperature using a lapse rate of 0.57 K per 100 m altitude, a theoretical mean Holocene temperature of 15.7°C would be expected for Reiarsdalsvatnet. The typical mean July temperature in the boreo-nemoral vegetation zone is 13°C to 17°C (Moen 1999). This all suggests that the general temperature level of the pollen-based reconstructions is likely to mirror the true conditions closer than the level of the chironomid-inferred temperatures.

The lower chironomid-based temperature reconstructions may be related to the prevailing existence of a profundal chironomid fauna in Reiarsdalsvatnet throughout the Holocene. This profundal fauna is dominated by *Sergentia* (cf., Chapter 5), which has a considerably lower temperature optimum (11.3°C as deduced from weighted averaging regression) than the mean Holocene chironomid-inferred temperature of Reiarsdalsvatnet. However, the presence of *Sergentia* only accounts for a minor part of the temperature difference (< 0.4 K), as can be seen from temperature reconstructions excluding *Sergentia*. Thus only a minor part of the temperature difference can be ascribed to the existence of a profundal fauna in Reiarsdalsvatnet. The high correlation of the pollen- and the chironomid-inferred temperatures demonstrates that the influence of the littoral chironomid taxa is strong enough to represent well Holocene variations in the mean July temperatures.

Between 8,500 cal. BP and 7,700 cal. BP, the reconstructed temperatures are apparently inversely correlated (*Fig. 6.5*). This period is part of the local assemblage zones RVpz 4 and RVchz 3 (*Fig. 4.11, 5.1*) and is not related to distinct changes in the pollen or chironomid assemblages. Moreover, it is a stable period according to the sediment proxies (*Fig. 4.15*). Thus this inverse relation can neither be explained by the reconstructed lake-internal processes, nor by the reconstructed catchment conditions. If it is a statistical artefact or may be related to undiscovered lake-internal processes or to climate changes in relation to the '8.2 ka event' (Alley *et al.* 1997) remains unsolved.

The period between 7,600 cal. BP and 6,500 cal. BP is the main phase of differences in the temperature reconstructions (*Fig. 6.5*). Here the chironomid-inferred temperatures are the more reliable ones as discussed above (*Fig. 6.1*). A third phase of temperature differences is obvious between 1,100 cal. BP and 600 cal. BP when only comparing the reconstructions conducted at the same sample depths (*Fig. 6.5*). Here, chironomid-inferred temperatures decrease, while pollen-inferred temperatures increase. Distinct changes expressed by the presence of zone boundaries are seen in the geochemical and the pollen data during this period (*Fig. 5.16*). The changes in these records are characterised by increasing, but moderate human impact and slightly increasing lake productivity (*Fig. 5.16*; cf., Chapter 5). Since these changes did not have a visible impact on the chironomid assemblages, it is assumed that the temperature decrease recorded in the chironomid-based reconstructions mirrors the true conditions well. The pollen-inferred temperatures most likely have been influenced by local factors other than temperature during this period and are thus regarded as less reliable than the chironomid-inferred temperatures (*Tab. A3*).

Isbenttjønn

In the Isbenttjønn profile (*Fig. 6.6*), the mean reconstructed Holocene temperature is 12.7°C for both the chironomid- and the pollen-inferred temperatures. The chironomid-inferred temperatures show a distinctly higher sample-to-sample variability than the pollen-based reconstructions (*Fig. 6.6*). These differences are one reason for the non-significance in the correlation analysis ($r = 0.13$, $p > 0.1$), which does not disappear when disregarding samples categorised as ‘less reliable’ ($r = 0.20$, $p > 0.1$). The relatively high between-sample variability of the chironomid-inferred temperatures is due to the ‘spiky’ curves of the chironomid percentages, especially obvious in the *Sergentia* curve (*Fig. 5.5*). The spikyness is not caused by the low head-capsule sums or the relatively large between-sample differences in head-capsule sum (minimum: 50, maximum: 145), since a comparison of count sums with the temperature reconstructions does not reveal any relation between extreme temperature values and low count sums. In addition, Heiri and Lotter (2001) found that the error which is produced when temperature reconstructions are based on low head-capsule sums (less than 50), is a systematic one resulting in either consistently too low or too high temperatures. Such a bias for temperature reconstructions based on low count sums cannot be seen in the Isbenttjønn profile. Another possibility to explain the spikyness of the chironomid-inferred temperatures would be a relation between the variability in the temperature reconstructions and internal-lake processes. If this was true, the spikes would mirror palaeoecological changes in Isbenttjønn, and the changes would have had a larger impact on the chironomid assemblage than mean July temperature. As seen from the results of Chapter 4 and 5, none of the proxies show such high frequency palaeoecological variations (*Fig. 4.16, 5.8, 5.16*). Thus, there is no evidence to explain such a high sample to sample variability in the palaeoecology of Isbenttjønn. The question why the chironomid-inferred temperatures reveal such a relatively high variability remains open.

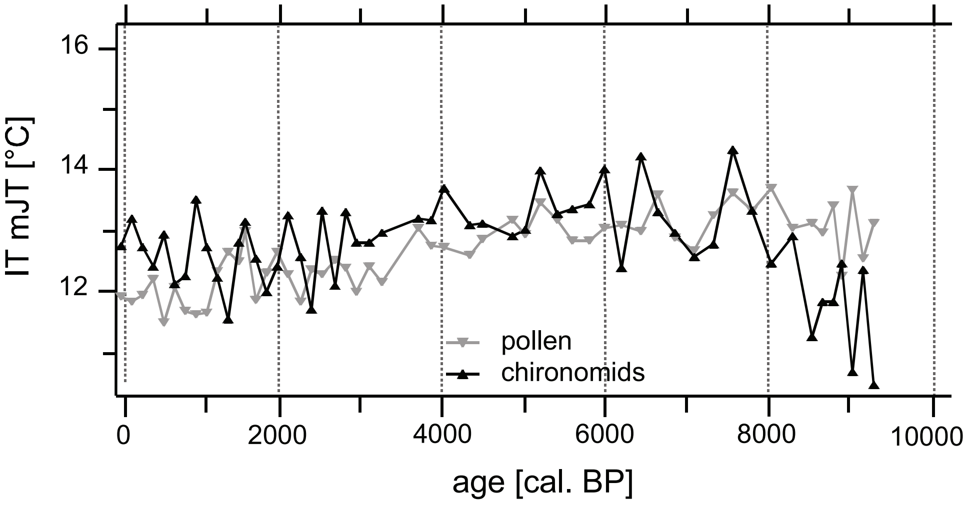


Figure 6.6: Chironomid- and pollen- inferred mean July temperatures for samples of Isbenttjønn. To enable a point-wise comparison of the temperatures, only samples with available chironomid- and pollen-inferred temperatures are shown.

Even though a point-wise correlation of chironomid- and pollen-inferred temperatures for Isbenttjønn is statistically insignificant as shown above, both temperature reconstructions show similar centennial to millennial-scale trends (*Fig. 6.5, 6.6*). The temperature differences before 9,000 cal. BP are, as discussed above, ascribed to statistical uncertainties in the pollen-inferred temperatures (*Fig. 6.2*) and the chironomid-inferred temperatures are regarded as being more reliable during this phase. The second phase of major temperature differences is the period after 1,300 cal. BP (*Fig. 6.4*), which is not related to uncertainties explained by the numerical evaluation criteria (*Fig. 6.2*). A change of factors influencing the chironomid assemblages since 1,300 cal. BP is indicated by the PCA, where sample scores on axis 1 and axis 2 generally show similar trends. Only after 1,300 cal. BP, both take an opposite course (*Fig. 5.15*). When performing a PCA excluding the chironomid samples younger than 1,300 cal. BP, only the first axis is significant in contrast to three significant axes in the original analysis (*Tab. 5.1*). This supports the assumption, that the chironomid assemblage is influenced by one major factor before 1,300 cal. BP and by different factors thereafter.

After 1,300 cal. BP chironomid-inferred temperatures are distinctly higher than pollen-inferred ones (*Fig. 6.6*). At the same time, major changes occurred in the lake (Chapter 5). The latter is recorded e.g., in the C:N ratios, carbon influx, and influx of total head-capsules and indicates slowly increasing lake productivity (*Fig. 4.9, 5.6, 5.17*). Brodersen and Anderson (2002) showed in a study of West Greenland lakes that the chironomid assemblages in those lakes react similar to increasing temperature and to increasing nutrient status. This may be true for Isbenttjønn after 1,300 cal. BP as well. The recorded increase in lake productivity, though being only moderate (Chapter 4), most likely had a larger impact on the chironomid assemblages than mean July temperatures did. Thus the chironomid-inferred temperatures are regarded as unreliable (*Tab. A3*) and the pollen-inferred temperatures as the reliable reconstructions during this phase.

Inter-site comparison

To develop a picture of the regional development of the Holocene summer temperatures, the temperature reconstructions of Reiarsdalsvatnet and Isbenttjønn are presented together in *Figure 6.7*, with phases of lower reliability (*Tab. A3*) marked by dashed lines and open symbols. When comparing the records, the uncertainties of the age-depth models have to be taken into account (Chapter 4, *Fig. 4.2, 4.5*). Thus the focus of the comparison of both records is on multi centennial-scale to millennial-scale temperature changes, not on short-term fluctuations.

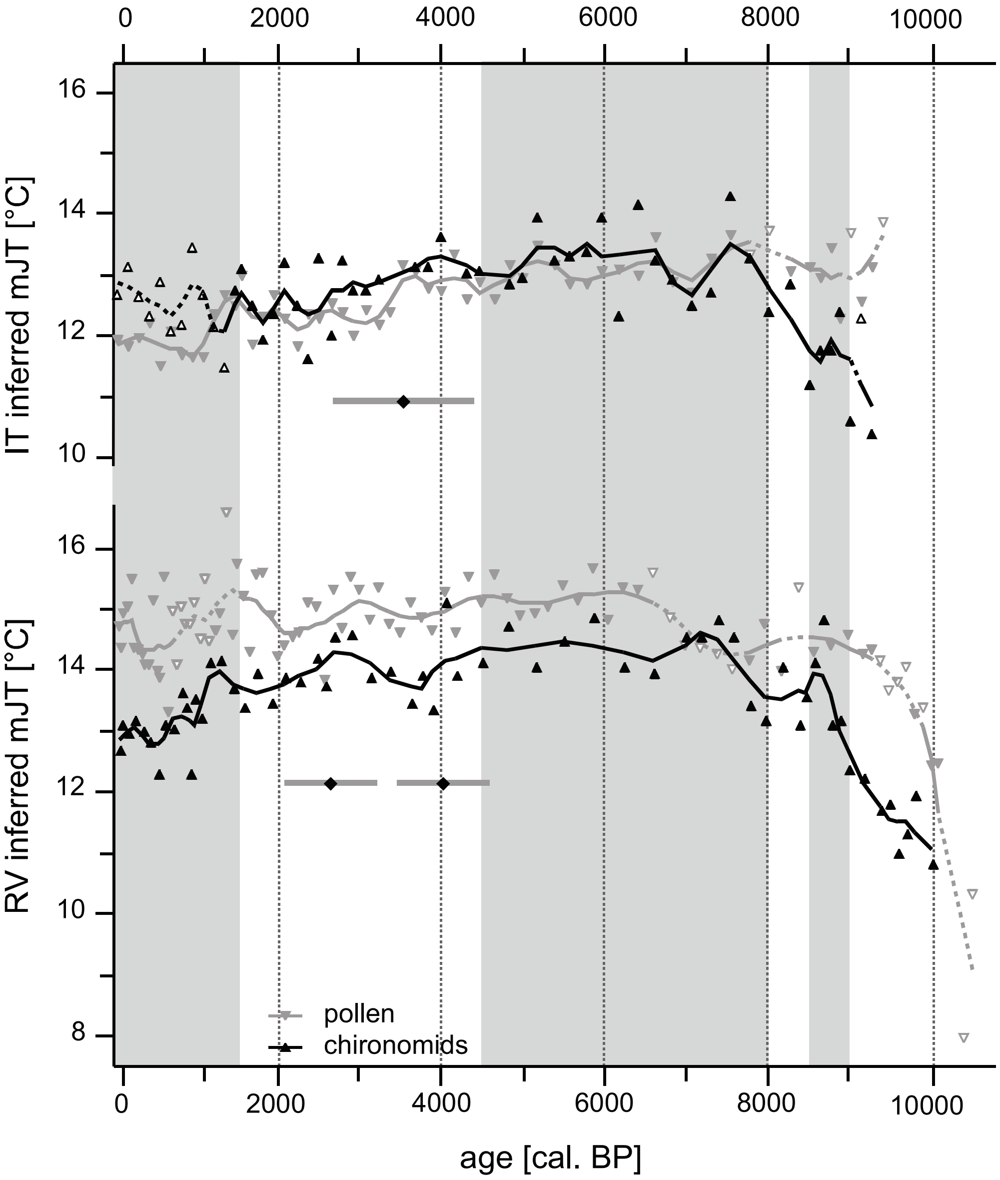


Figure 6.7: Chironomid- and pollen-inferred mean July temperatures (mJT) for Reiarsdalsvatnet (RV) and Isbenttjønn (IT). The reconstructed temperatures are shown as symbols, the century-scale temperature trends are highlighted by a LOWESS smoother (bold line). Phases where the reconstructed temperatures are of lower reliability are marked by dashed LOWESS smoothers and open symbols. Uncertainties of the age-depth model are shown for three samples with the modelled age indicated by black diamonds and the 95% confidence interval by grey bars. Grey and white background refers to periods discussed in the text.

The multi centennial- and millennial-scale temperature changes show a surprising coherency between those parts of the reconstructed mean July temperatures in Reiarsdalsvatnet and Isbenttjønn that are considered as reliable (*Fig 6.7*). While many data points of the pollen-inferred temperatures before 8,000 cal. BP are ‘less reliable’, the chironomid-based reconstructions show a stepwise temperature increase during this time, with a positive peak around 8,700 cal. BP. The records reach Holocene maximum temperatures around 7,500 cal. BP. Temperatures remain stable and high until

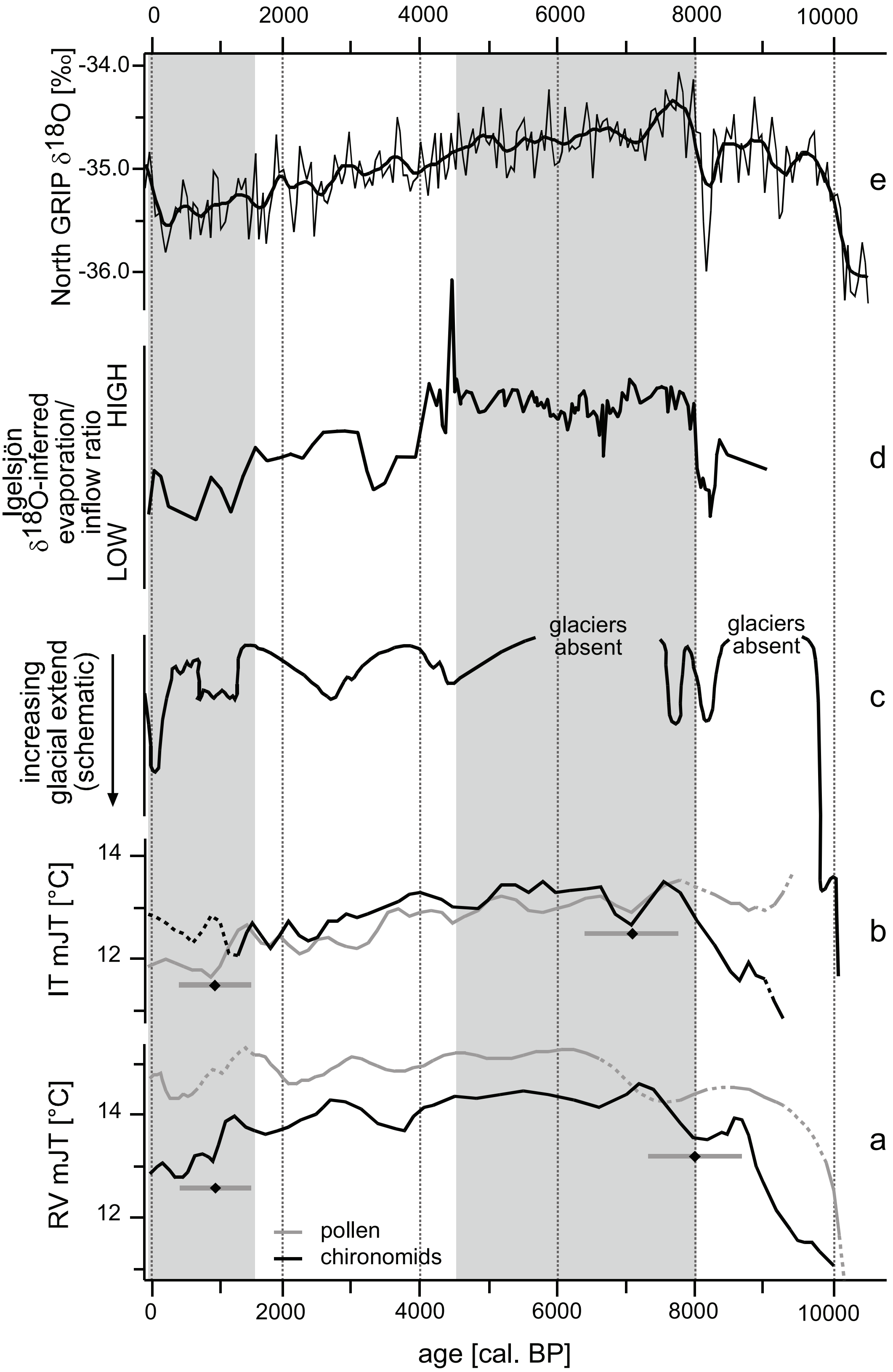
c. 4,500 cal. BP in all four records, whereas decreasing temperatures and larger differences between the records of the two lakes can be observed between 4,500 cal. BP and c. 1,500 cal. BP. A positive temperature peak is seen around 1,500 cal. BP in all records, and all but the chironomid-inferred temperatures from Isbenttjønn drop to distinctly lower temperatures thereafter. The comparison between the temperature reconstructions of both sites supports the usefulness of applying the evaluation procedures described above. By doing so, it is possible to define phases of unreliable reconstructions like e.g., the chironomid-based reconstructions after 1,300 cal. BP in the Isbenttjønn record, and thus increase the coherency of the reconstructions of both sites, which is high compared to other studies (Rosén *et al.* 2003, Rosenberg *et al.* 2004, Velle *et al.* 2005a).

Several authors have pointed out the importance of muli-site studies to provide a more reliable and coherent pattern of climate change reconstructions (e.g. Heinrichs *et al.* 2006, Larocque and Hall 2004, Velle *et al.* 2005a). However, the main problem of Holocene multi-site studies is the precision of the age-depth models. In the present study, due to the uncertainties of the age-depth model it cannot be decided if e.g., the temperature decrease in the pollen-inferred data at 3,500 cal. BP in Isbenttjønn is related to the decrease in temperatures at 4,000 cal. BP or the one at 2,600 cal. BP in Reiarsdalsvatnet (*Fig. 6.7*). Even though the uncertainties in the Reiarsdalsvatnet and Isbenttjønn profiles are relatively large due to the low number of radiocarbon dates and due to the dated bulk material, the 95 % confidence intervals of age-depth models based on radiocarbon dates mostly fall in the range of one to several centuries (Heegaard *et al.* 2005, Telford *et al.* 2004). Thus multi-site studies of climate variations are limited by the age-depth model uncertainties and in most cases cannot be used to evaluate climate variations lasting only a few centuries or less. Especially when following a consensus approach (Palmer *et al.* 2002, Velle *et al.* 2005a), only (multi-) millennial-scale changes in temperatures can be deduced.

Regional and supra-regional comparisons with independent palaeoclimatological records

For a further validation of the reconstructed temperatures at Reiarsdalsvatnet and Isbenttjønn, the records are compared to other palaeoclimatological records (*Fig. 6.8*). These other records need to be independent from the chironomid- and pollen-based reconstructions, thus chironomid- and pollen-based summer temperature reconstructions from Scandinavia were not taken into account as primary records for comparison (e.g. Korhola *et al.* 2002, Larocque 2004, Larocque and Hall 2004, Rosén *et al.* 2003, Rosén *et al.* 2001, Seppä and Birks 2001, Seppä *et al.* 2005, Velle *et al.* 2005a). These palaeotemperature records are methodologically not independent from the Reiarsdalsvatnet and Isbenttjønn reconstructions, as they are based on the same statistical methods and on the same or overlapping modern calibration data-sets. In addition, they face the same possibility of biased reconstructions due to influences other than temperature on the chironomid assemblages. Thus the following independent palaeoclimatic records were chosen as primary records for comparison (*Fig. 6.8*):

- Holocene glacier variations in central Jotunheimen (southern Norway) (Matthews *et al.* 2005) (*Fig. 6.8 c*), which have been reconstructed based on the lithostratigraphical analyses of two alpine mires in proximity to the glacier Bjørnbreen. The mires have been flooded episodically by melt water and glacier variations are reconstructed by the analysis of multiple sedimentological indicators. The chronology is based on 56 calibrated radiocarbon dates. Since the studied glacier is more continental than many other glaciers in southern Norway, e.g., Folgefonna (Bakke *et al.* 2005) or Hardangerjøkulen (Dahl and Nesje 1994), its net mass balance in large part is controlled by summer temperatures, in contrast to the more maritime glaciers which are mainly controlled by winter precipitation (Nesje *et al.* 2000; Sejrup *et al.* 2000).
- Palaeohydrological changes, which have been reconstructed by the analysis of stable isotopes ($\delta^{18}O$ on bulk carbonate) at Igelsjön, southern Sweden (Hammarlund *et al.* 2003), (*Fig. 6.8 d*). The original chronology of this record is based on 22 calibrated radiocarbon dates from terrestrial macrofossils (Hammarlund *et al.* 2003). In *Figure 6.8 d*, the modified chronology according to an additional 8 radiocarbon dates from macrofossils is shown (Jessen *et al.* 2005). In the period after 9,000 cal. BP, the $\delta^{18}O$ signal in this record is interpreted as a combined temperature and precipitation signal (Hammarlund *et al.* 2003). Higher $\delta^{18}O$ values are due to drier and/or warmer climate, lower values are a signal of more humid and/or colder climate. Hammarlund *et al.* (2003) conclude that summer temperature is the most important variable in the period from 9,000 cal. BP to 4,000 cal. BP, while increased precipitation is more important after 4,000 cal. BP.
- Former ice-surface air temperatures, which have been inferred from the $\delta^{18}O$ record in incremental ice layers from NorthGRIP (central Greenland; *Fig. 6.8 e*; Johnsen *et al.* 2001). The chronology of the NorthGRIP record is based on annual layer counting. This record was chosen since it shows a stronger signal and a clearer mid-Holocene climatic optimum than the GRIP record does (Johnsen *et al.* 2001).


0
2000
4000
6000
8000
10000
North GRIP δ18O [‰]
-34.0
-35.0
-36.0
e
Igelsjön δ18O-inferred evaporation/ inflow ratio
HIGH
LOW
d
increasing glacial extend (schematic)
glaciers absent
glaciers absent
c
IT mJT [°C]
14
12
b
RV mJT [°C]
14
12
a
pollen
chironomids
age [cal. BP]

Early Holocene (before 8,000 cal. BP)

The NorthGRIP $\delta^{18}O$ record and the record of the glacier variations indicate a rapid temperature increase around 10,000 cal. BP and relatively high temperatures between 9,800 cal. BP and 8,300 cal. BP (*Fig. 6.8*). The rapid temperature increase marks the end of the 'Erdalen event', which has been widely recognised in southern Norway (Dahl and Nesje 1994, Nesje 1997, Nesje and Kvamme 1991) and has been dated to 9,700 cal. BP at Jostedalsbreen, western Norway (Dahl et al. 2002). During this phase, the lake formation of Reiarsdalsvatnet (c. 10,100 cal. BP) and Isbenttjønn (9,300 cal. BP) took place (Chapter 4). Both chironomid-based temperature reconstructions show an increasing trend and reach temperatures comparable to those of the youngest millennium at 9,000 cal. BP. The positive temperature peak around 8,700 cal. BP occurs together with a first local maximum in the NorthGRIP $\delta^{18}O$ record (*Fig. 6.8*). The pollen-inferred temperatures in both profiles are distinctly higher, but they are statistically less reliable than the chironomid-inferred temperatures. The more gradual increase in chironomid-inferred temperatures compared to both the NorthGRIP $\delta^{18}O$ record and the record of glacier variations can be explained by different processes. The palaeoecological reconstructions revealed that typical Holocene lake conditions were established by 9,600 cal. BP in Reiarsdalsvatnet and by 8,600 cal. BP in Isbenttjønn (*Fig. 5.16, 5.17*). Thus the temperature reconstructions during this phase might be biased due to lake-internal processes, even though the numerical evaluation criteria did not indicate such a bias. The more gradual increase in chironomid-inferred temperatures may also be due to uncertainties in the age-depth models (*Fig. 4.2, 4.5*), which show largest uncertainties in the phase between 10,000 cal. BP and 9,000 cal. BP and thus may explain the 'delayed' temperature increase. However, it may as well mirror the true development of mean July temperatures, as other pollen-based temperature reconstructions from south-western Norway (mean July temperature, Bjune *et al.* 2005) and southern Finland (mean annual temperature, Heikkilä and Seppä 2003) show the same gradual temperature increase during this period.

← *Previous page*

Figure 6.8: Chironomid- and pollen-inferred mean July temperatures (mJT) for a) Reiarsdalsvatnet (RV) and b) Isbenttjønn (IT), (LOWESS smoothers, dashed parts indicate lower reliability), together with c) a record of Holocene glacier variations at Bjørnbreen, central Jotunheimen, southern Norway (Matthews et al. 2005), d) palaeohydrological changes recorded in the stable isotopes ($\delta^{18}O$ on bulk carbonate) at Lake Igelsjön, southern Sweden (Hammarlund et al. 2003), and e) former ice-surface air temperatures inferred from the $\delta^{18}O$ record in incremental ice layers from NorthGRIP, central Greenland (Johnsen et al. 2001). Uncertainties of the age-depth models of Reiarsdalsvatnet and Isbenttjønn are shown for four samples with the modelled age indicated by black diamonds and the 95% confidence interval by grey bars. Grey and white background refers to periods discussed in the text.

The centennial-scale cold event around 8,000 cal. BP, known as the '8.2 ka event' from the central Greenland ice cores (Alley *et al.* 1997) and as the 'Finse event' from Norway (Nesje and Dahl 2001), is visible in all three records chosen for the validation of the chironomid-inferred temperatures (*Fig. 6.8*). In their review article, Rohling and Pälike (2005) distinguish the short '8.2 ka event' from a widespread, multi-century climatic deterioration between c. 8,500 cal. BP and 8,000 cal. BP and state that the first one is due to a sharp decrease in winter temperature, while the latter one is related to a longer lasting period of reduced summer temperatures. In Reiarsdalsvatnet and Isbenttjønn, the lower chironomid-inferred temperatures during this period may be related to this event (*Fig. 6.8*). However, this relation remains uncertain due to the low resolution of the Isbenttjønn record during this phase (*Fig. 4.8*) where only three samples represent the interval from 8,500 cal. BP to 8,000 cal. BP (*Fig. 6.7).* A synchronicity of the Isbenttjønn cold period centred at 7,000 cal. BP and the '8.2 ka event' in the NorthGRIP record can be excluded due to the uncertainties of the age-depth model (*Fig. 6.8*).

Holocene thermal maximum (8,000 cal. BP to 4,500 cal. BP)

The period of maximum Holocene temperatures is seen between 8,000 cal. BP and 4,500 cal. BP in the temperature reconstructions from Reiarsdalsvatnet and Isbenttjønn and in the other shown palaeoclimatic records (*Fig. 6.8*). It has also been recognised in numerous other records from Scandinavia (e.g. Bjune *et al.* 2005, Heikkilä and Seppä 2003, Nesje 1997, Seppä *et al.* 2005). Highest inferred temperatures are reached around 7,300 cal. BP in Reiarsdalsvatnet and around 7,500 cal. BP in Isbenttjønn, which can be related to the maximum values at 7,700 cal. BP in the NorthGRIP $\delta^{18}O$ record (*Fig. 6.8*). In addition, the high $\delta^{18}O$ values in the Igelsjön record during this phase (*Fig. 6.8*) are most likely caused by relatively high summer temperatures and to a lesser extend by low amounts of precipitation (Hammarlund *et al.* 2003). Stable maximum temperatures observed in the Reiarsdalsvatnet and the Isbenttjønn records support the assumption that the atmospheric polar front shifted northwards during this phase (Johnsen *et al.* 2001), and summer temperatures in southern Scandinavia were influenced by blocking anticyclonic conditions, which lead to dry and warm summers (Seppä *et al.* 2005).

The short-term decrease in chironomid- and pollen-inferred temperatures in the Isbenttjønn record at 7,000 cal. BP is resembled by lower values in the NorthGRIP $\delta^{18}O$ record (*Fig. 6.8*) but less clearly in the other records (*Fig.* 6.8). In the $\delta^{18}O$ Igelsjön record, a brief period of lower values is apparent at 6,700 cal. BP (Hammarlund *et al.* 2003). It is not possible to decide if these fluctuations represent the same event, which would indicate regional significance, on the basis of the available records (*Fig. 6.8*).

Climate deterioration (4,500 cal. BP to 1,500 cal. BP)

After 4,500 cal. BP a change in the broad-scale climate has been observed in many climate archives, e.g., by a lowering of the tree-line in western Norway (Bjune 2005). This is also visible in *Figure 6.8*, where decreasing mean July temperatures in Reiarsdalsvatnet and Isbenttjønn occur together with increasing glacier activity as recorded in Bjørnbreen, increasing net precipitation seen in the Igelsjön record, and decreasing NorthGRIP $\delta^{18}O$ values. Though Hammarlund *et al.* (2003) state that it remains unresolved if the inferred increase in net precipitation in Igelsjön during this time is due to increasing precipitation or decreasing temperature or a combination of both, the inferred temperatures for Reiarsdalsvatnet and Isbenttjønn suggest that a general temperature decrease took place. Lower temperatures, especially during winters, are as well indicated from archaeological evidence, as the 'langhus' houses have been found since c. 3000 cal. BP (Myhre 2004), where animals were kept inside during winter. The colder climate is most likely connected to a sudden break-up of the stable anticyclonic conditions around 4,300 cal. BP, increased influence by the zonal flow, and a further gradual cooling towards the present (Seppä *et al.* 2005).

Later Holocene (after 1,500 cal. BP)

The period after c. 1,500 cal. BP covers the known phases of the 'Medieval Warm Epoch' (Lamb 1965), the climate deterioration of the 'Little Ice Age', and the warming during the 20th century. The inferred temperatures during this time are characterised by relatively high values around 1,500 cal. BP and a sudden drop between c. 1,500 cal. BP and 1,100 cal. BP to distinctly lower values. This is shown in the Igelsjön record and the glacial advances in Bjørnbreen (*Fig. 6.8*). The sudden decrease in summer temperatures can also be seen in other biological proxy-based temperature reconstructions from southern Scandinavia (e.g. Bjune *et al.* 2005, Hammarlund *et al.* 2004, Heikkilä and Seppä 2003, Seppä *et al.* 2005).

The glacier advances of the 'Little Ice Age', which were the largest since the early Holocene in Norway, reached their maximum extent after 500 cal. BP (Nesje 2002). This is in line with the inferred temperatures of Reiarsdalsvatnet and Isbenttjønn, where low temperatures are recorded during the last millennium (*Fig. 6.8*). Only before c. 8,500 cal. BP were such low values observed. The increased warming in the 20th century, which has been inferred by the widely discussed Mann *et al.* reconstructions (Mann 1999, Mann *et al.* 1998), is not seen in the inferred temperatures, which is most likely due to the low resolution of the record, with three samples representing the last century in Reiarsdalsvatnet and only one sample in Isbenttjønn.

Comparison with Holocene chironomid-inferred temperature reconstructions from southern Norway

Using different evaluation procedures, it was possible to demonstrate that the chironomid-based temperature reconstructions from Reiarsdalsvatnet and Isbenttjønn resemble known Holocene temperature trends well (see above). Thus subfossil chironomids from the studied non-alpine sites do react sensitively to Holocene small-scale summer temperature fluctuations. To assess how these results compare to previously published chironomid-inferred temperatures from high altitude sites, they are discussed referring to the study from Velle *et al.* (2005a). In this study the authors compare six records of chironomid-based Holocene temperature reconstructions from southern Norway, all situated in the low-alpine vegetation zone. Some of these records have been published in more detail before (cf. Brooks 2003, Hammarlund *et al.* 2004, Velle *et al.* 2005b). Two of these sites (Vestre Øykjamyrtjørn and Holebudalen) are situated within a distance of less than c. 100 km from Isbenttjønn, while the other four records are located further north. Velle *et al.* (2005a) found major discrepancies in the Holocene mean July temperature reconstructions among the sites. This is especially evident in the comparison of the records of Vestre Øykjamyrtjørn and Holebudalen (Velle *et al.* 2005a). While the reconstructed temperatures in Holebudalen are highest in the early Holocene, decrease distinctly between 8,000 cal. BP and 5,000 cal. BP, and decrease more slowly thereafter, the temperatures in Vestre Øykjamyrtjørn are lowest in the early Holocene, rise distinctly between 8,000 cal. BP and 6,000 cal. BP, and remain constant thereafter. Comparable differences are observable between all six temperature reconstructions. The general temperature trends found in Reiarsdalsvatnet and Isbenttjønn i.e., increasing temperatures until c. 8,000 cal. BP, stable and high temperatures until c. 4,500 cal. BP, slowly decreasing temperatures after 4,500 cal. BP, and a sudden drop in temperatures after 1,500 cal. BP are only partly seen in some of the reconstructions from the low-alpine sites. Thus the palaeotemperature records of Velle *et al.* (2005a) exhibit distinctly less coherency than the Reiarsdalsvatnet and Isbenttjønn records do. Velle *et al.* (2005a) explain these discrepancies by different local factors influencing the chironomid assemblages, such as melt-water inflow from snow-beds, productivity changes, and water chemistry changes. For future studies, they suggest a careful site-selection, preferably choosing sites in which the vegetational and catchment changes are minimal. The results of the study of Reiarsdalsvatnet and Isbenttjønn support this suggestion, since it was demonstrated at these sites that local factors play a minor role during most of the Holocene and that summer temperatures can be reconstructed properly based on the analyses of chironomid assemblages.

Conclusions

1. In this Chapter, chironomid-inferred Holocene mean July temperatures have been reconstructed from sediments of two non-alpine lakes. By the application of different evaluation procedures, it was possible to differentiate between phases of reliable and phases of less reliable temperature reconstructions.
2. It is inferred that human impact resulting in increased lake productivity most likely is responsible for a phase of unreliably high chironomid-based temperature reconstructions in the youngest sediments of Isbenttjønn, even though the increase in productivity was moderate and the trophic state of the lake did not increase distinctly.
3. Leads and lags between chironomid- and pollen-inferred temperatures could not be reconstructed. Even though chironomids and vegetation are expected to need different amounts of time to react on changes in temperature (Lotter 2003) these differences are small compared to the rates of centennial to millennial temperature fluctuations (cf. Ammann 2000).
4. Limiting factors for century-scale temperature reconstructions are the uncertainties of radiocarbon-based age-depth models and the limitation caused by the absolute number of sub-samples per century.
5. The chironomid-inferred temperatures of both lakes show similar trends over the Holocene, with increasing temperatures until c. 8,000 cal. BP, maximum Holocene temperatures between 7,600 cal. BP and 7,200 cal. BP, stable and high temperatures until c. 4,500 cal. BP, slowly decreasing temperatures after 4,500 cal. BP, and a clear drop in temperatures after 1,500 cal. BP. These trends resemble widely known features of the Holocene summer temperature development in Scandinavia, as assessed by the comparison to records of Norwegian Holocene glacier variations (Matthews *et al.* 2005), of Holocene changes in net precipitation in southern Sweden (Hammarlund *et al.* 2003), and of inferred air temperatures in central Greenland (Johnsen *et al.* 2001). Thus it was shown that subfossil chironomids from the non-alpine sites studied do react sensitively to small-scale summer temperature fluctuations.
6. The palaeotemperature records of the non-alpine sites Reiarsdalsvatnet and Isbenttjønn show distinctly more site-specific and between-site coherency than the chironomid-based palaeotemperature records from low-alpine sites studied by Velle *et al.* (2005a).
7. The applied procedure of temperature reconstruction and evaluation showed that both lakes are appropriate sites for the chironomid-based reconstruction of small-scale temperature fluctuations. However, the reliability of the reconstructed

temperatures can only be assessed with a thorough knowledge about the palaeoecology of the lakes and the application of different evaluation procedures. Only with all of the applied procedures was it possible to differentiate between phases where temperature exerted the most important influence on the chironomid assemblages and phases when other local factors played a major role.

Chapter 7: Conclusions and Outlook

The aim of this study was to evaluate the appropriateness of lakes located below modern tree-line for quantitative chironomid-based reconstructions of Holocene summer temperature variations. For this, the sediments of the two non-alpine lakes Reiarsdalsvatnet and Isbenttjønn (cf. Chapter 2) were studied including chironomid and pollen analyses, and analyses of geochemical parameters.

Initial questions and hypotheses

In Chapter 1, three main questions are given for this study. The point of the first questions is, whether the water chemistry and physical conditions of non-alpine lakes can be regarded as stable during the Holocene (Chapter 1). Based on the analyses of pollen, chironomids and geochemical parameters, it was demonstrated that soil stability in the catchment of Reiarsdalsvatnet was reached by 9,600 cal. BP, and by 8,600 cal. BP in the catchment of Isbenttjønn (*Fig. 5.16, 5.17*). Thereafter, no erosional events are observed in the sediments of any of the lakes (Chapter 4). This demonstrates that the input of particulate matter into both lakes was stable at a low level during the last 9,600 and 8,600 years, respectively. From the chironomid record, it is shown that well oxygenated conditions in the hypolimnion of Reiarsdalsvatnet and good to moderate hypolimnetic oxygenated conditions for Isbenttjønn prevailed during the Holocene (Chapter 5). The input and availability of nutrients in the lake was also stable, since only gradual changes in the trophic conditions of the lakes occurred during the Holocene with Isbenttjønn remaining oligotrophic and Reiarsdalsvatnet oligo- to mesotrophic (*Fig. 5.16, 5.17*; Chapters 4 and 5).

Slowly changing conditions in the lakes and their catchments are indicated by the tendency towards increasing dystrophication observed in the topmost sediments of Reiarsdalsvatnet and over most of the Isbenttjønn profile. Moreover, an increasing opening of the landscape since 2,700 cal. BP at Reiarsdalsvatnet and since 1,400 cal. BP at Isbenttjønn was inferred from the pollen data, in both cases most likely connected to human activity (*Fig. 5.16, 5.17*). However, these alterations generally are not abrupt but occurred gradually (Chapter 5). The only exception is the one at 1,400 cal. BP in Isbenttjønn, where changes in the catchment are paralleled by changes in the chironomid assemblages and in the geochemical data (*Fig. 5.16, 5.17*). Apart from this period, both lakes have undergone only minor changes.

To assess the absolute dimension of these changes, they need to be compared to changes in lakes located at or above the modern tree line. However, a direct comparison of Reiarsdalsvatnet and Isbenttjønn with lakes, which are located at higher altitudes or latitudes and have been study-sites for Holocene chironomid-based temperature reconstructions, is difficult. Many of the publications do not include additional information about the development of the catchment or the lake derived from non-biological data and are thus not comparable extensively (e.g. Heiri *et al.* 2003b, Larocque 2004, Larocque and Hall 2004, Palmer *et al.* 2002, Rosén *et al.* 2001, Rosenberg *et al.* 2004). The sediment proxy most often published together with chironomid-inferred temperatures is the organic content of the sediment, analysed as loss-on-ignition (LOI, Chapter 3). In the Reiarsdalsvatnet and the Isbenttjønn profiles, LOI values are stable after 8,900 cal. BP and 8,600 cal. BP, respectively (*Fig. 4.3, 4.6*). Compared to these records, five of the six low-alpine lakes studied by Velle *et al.* (2005a) exhibit distinctly larger amplitudes in the LOI fluctuations during the last 9,000 years. In one of these lakes, the impact of the forest retreat on the aquatic ecosystem was reconstructed in detail and distinct changes in primary productivity due to changing vegetation around the lake were recorded in the LOI values (Hammarlund *et al.* 2004). Dalton *et al.* (2005) also show in their multi-proxy study of a lake located above the potential tree-line in north-east Scotland that catchment-driven changes due to the development and degradation of soils had a major impact on the lake. These changes are mirrored by distinct fluctuations in the LOI record (Dalton *et al.* 2005), which are large compared to the ones of the Reiarsdalsvatnet and Isbenttjønn records. From this comparison it is inferred that the water chemistry and the physical conditions in Reiarsdalsvatnet and Isbenttjønn have even undergone only minor changes during the studied period. Therefore hypothesis 1, saying that ‘water chemistry and physical conditions of the studied lakes were only subject to minor changes during the Holocene, and can thus be regarded as stable’ (Chapter 1) is accepted.

The second question of this study asks, whether chironomid assemblages in lakes situated below modern tree-line react sensitively to Holocene temperature fluctuations (Chapter 1). In different studies about chironomid calibration data-sets, other factors than climate have been found to influence chironomid assemblages. The most important ones are organic content (LOI) and lake depth (Olander *et al.* 1999), hypolimnic oxygen levels (Little and Smol 2001, Quinlan and Smol 2002), and nutrients (Brooks *et al.* 2001). When regarding these factors for Reiarsdalsvatnet and Isbenttjønn, the following can be shown: It has been demonstrated that no major changes in organic content of the sediments occurred, as discussed above (*Fig. 4.9, 4.10*). No signs of significant lake level changes were found and since the sedimentation rates are low, the lake depths only decrease little due to infilling of the lakes (Chapter 4). The hypolimnic oxygen levels were good to moderate during the Holocene and chironomids typical of oxygen depletion were only found in very low numbers (*Fig. 5.3, 5.5*; Chapter 5). During the Holocene, the nutrient availability in both lakes was low and changed only moderately (*Fig. 5.16, 5.17*; Chapters 4 and 5). Moreover, the results of the chironomid analyses and the chironomid-based temperature reconstructions demonstrate that the chironomid assemblages and the vegetation in the catchments were generally independent (Chapter 5 and 6). Thus these local factors can be excluded as major cause of the changes in the chironomid assemblages. The only exceptions are the youngest sediments of Isbenttjønn (after 1,300 cal. BP), where it was demonstrated that the changes in the chironomid assemblages are connected to changes in the pollen record and in the geochemical data (*Fig. 5.17*; Chapter 5). The comparison between the chironomid-inferred temperatures and independent palaeoclimate data suggests that in both lakes changes in the chironomid assemblages were not triggered by temperature and are thus due to catchment-driven or lake internal processes (Chapter 6). Apart from the latter period in Isbenttjønn, the chironomid-inferred temperatures of both lakes show similar trends over the Holocene (*Fig. 6.7*). These trends resemble widely known features of the Holocene summer temperature development in Scandinavia (*Fig. 6.8*; Chapter 6) and show distinctly more site-specific and between-site coherency than the chironomid-based palaeotemperature reconstructions from the low-alpine sites from southern Norway studied by Velle *et al.* (2005a). Summarising the discussed facts, it is concluded that subfossil chironomids from Reiarsdalsvatnet and Isbenttjønn react sensitive to small-scale Holocene summer temperature fluctuations. For this reason hypothesis 2 (Chapter 1), stating that 'the small-scale fluctuations of Holocene summer temperatures are recorded in the subfossil chironomid records of the studied lakes' is accepted.

The third question posed in Chapter 1 asks, whether subfossil chironomids from non-alpine lakes record human impact. Charcoal found in the pollen data has been used to assess human impact in the catchment of Reiarsdalsvatnet and Isbenttjønn (Chapter 4) and two periods of higher charcoal values have been found. In Reiarsdalsvatnet, elevated charcoal values between c. 9,500 cal. BP and c. 6,500 cal. BP (Mesolithic) are likely to indicate first human activity close to the lake, even though it only had minor impact on the vegetation (*Fig. 4.15*; Chapter 4). The second period of elevated charcoal values starts at 3,300 cal. BP in Isbenttjønn and at 2,700 cal. BP in Reiarsdalsvatnet with highest values being reached after 1,300 cal. BP in Isbenttjønn and after 700 cal. BP in Reiarsdalsvatnet (*Fig. 4.15, 4.16, 5.16, 5.17*). Here, it was inferred from the multi-proxy analysis of the sediments and the different validation procedures that in Reiarsdalsvatnet the local human activity did not have a major impact on the chironomid assemblages (Chapter 5 and 6). In contrast to this, human activity most likely had a major influence on the chironomid assemblages in the sediments of Isbenttjønn after 1,300 cal. BP, where the reconstruction results in unrealistic high temperatures (*Fig. 6.7*; Chapter 6). The fact that the chironomid-assemblages in Isbenttjønn were stronger influenced by the recorded human impact than in Reiarsdalsvatnet may be explained by the following reasons. Human impact around Isbenttjønn was most likely stronger than around Reiarsdalsvatnet. As discussed in

Chapter 2, archaeological evidence for iron and charcoal production dated to the period between 1,400 cal. BP and 580 cal. BP (Bloch-Nakkerud 1987, Martens 1988) has been discovered in the upper part of Setesdal and in Vinje (Telemark), suggesting local human presence. In addition, it is known that the whole area around Isbenttjønn was used for pasture by cows and goats during many centuries (U. Høydal 2006, pers. comm.). This kind of land use most likely intensified the influx of particulate and dissolved matter into Isbenttjønn. Since the trophic status of Isbenttjønn has naturally been low, already small changes in the influx were able to trigger changes in the aquatic system. Contrary to Isbenttjønn, archaeological evidence from the region around Reiarsdalsvatnet is sparse. Generally it is known that farmers have been permanently settled in Setesdal by c. 1,500 cal. BP (Larsen 1981). However, the local human impact was most likely less intensive around Reiarsdalsvatnet compared to Isbenttjønn, since the area was not typically used for pasturing or iron and charcoal production, and since the growing of cereals only played a very minor role (Chapter 4). Moreover, human impact like one caused by forest pasturing was most likely buffered by the dense forests around Reiarsdalsvatnet. This caused the chironomid assemblages in Reiarsdalsvatnet not to react as sensitive to the local human activity as in Isbenttjønn. Because of these different impacts of human activity in Reiarsdalsvatnet and Isbenttjønn, no consistent answer can be given to the initial question, and hypothesis 3 saying that 'the subfossil chironomid records of the studied lakes are not influenced by human impact' is rejected.

The chironomid-inferred temperatures of both lakes generally resemble the temperature trends widely known from Scandinavia, with increasing temperatures until c. 8,000 cal. BP, maximum Holocene temperatures around 7,500 cal. BP, stable and high temperatures until c. 4,500 cal. BP, slowly decreasing temperatures after 4,500 cal. BP, and a drop in temperatures after 1,500 cal. BP (*Fig. 6.8*). These findings support the results of Larocque and Hall (2003), who conclude that 'chironomids are sensitive enough to record changes of low magnitude during the Holocene, and should not be considered as a powerful tool only for the Late-Glacial period'. The present study adds to this statement that non-alpine lakes are high potential sites for the reconstruction of small-scale temperature variations based on chironomids. They may even be more adequate sites for chironomid-based temperature reconstructions than lakes from the tree-line ecotone, which are especially sensitive to climate changes reflected in the diatom assemblages (Lotter *et al.* 1999). Moreover, the present study points to the importance of a cautious selection of study sites and to the fact that a thorough knowledge about the catchment-lake system and a thorough evaluation of the reconstructed temperatures is crucial to obtain reliable results.

Implications for future research

This study demonstrates the potential of Holocene quantitative chironomid-based temperature reconstructions based on sediments from lakes located below modern tree-line. From these results, several propositions for future research are derived.

Most obvious is the need for more studies of lakes comparable to Reiarsdalsvatnet and Isbenttjønn. Such an extension of the present study will be especially valuable if it will be done regionally, i.e., in Setesdal, to maximise the between-lake similarity. A study of lakes located at altitudes in between Reiarsdalsvatnet and Isbenttjønn will add knowledge about the influence of different vegetation zones to the lake systems and the chironomid assemblages. Such a study will as well contribute to solve the question studied by Heegaard *et al.* (2006), if and where chironomid ecotones exist. A larger number of chironomid-inferred temperature profiles derived from non-alpine lakes will also form a reliable basis to evaluate the conclusion drawn from the present study that non-alpine lakes are appropriate sites for chironomid-based reconstructions of small-scale temperature variations. In a further step, non-alpine lakes from different regions need to be studied to answer the question, whether the presented results are also valid for other regions. Such multi-site studies will give a more coherent picture of the regional patterns of Holocene summer temperatures. However, as discussed in Chapter 6, multi-site studies of climate variations are limited to the uncertainties of the age-depth models. These uncertainties cause a limitation in the interpretable periods of temperature variability and often only (multi-) millennial-scale changes can be interpreted from a statistical point of view.

Even though the present study gives promising results, the two studied lakes are not sufficient as basis for the derivation of general recommendations for site selection. However some suggestions can be made for the choice of future study sites for studies intending to reconstruct small-scale temperature variations based on chironomids. The catchments of the lakes should have been densely vegetated or forested throughout the period of interest and human activity should not have had strong effects on the vegetation. Eutrophic lakes should be avoided because they most likely have experienced major changes in the intensity of the lake internal productivity over longer periods of time. Moreover, the sedimentation rates in eutrophic lakes are relatively high, thus the lakes change over time by the infilling of sediments. This may have major effects on the stratification of the water column and on the ratio of littoral to profundal area, which plays a major role in the ecology of chironomids.

One result of the comparison of the Reiarsdalsvatnet and Isbenttjønn profiles is that human activity had a more severe impact on the higher altitude Isbenttjønn than on Reiarsdalsvatnet, as discussed above. This supports results of a palaeolimnological study in the Swiss Alps by Heiri and Lotter (2003), who found prehistoric human activity having had a major impact on the chironomid assemblages. They conclude 'that alpine lake ecosystems can be extremely sensitive to human activity in the catchment' (Heiri and Lotter 2003). Thus the assumption that the remoteness of high altitude sites assures minor human impact, which makes these lakes adequate sites for climate reconstructions, is not straight forward and in certain cases may be wrong. In future studies, the reconstruction of the lakes ecological development (cf. Chapters 4 and 5) should always be included as basis for the interpretation of the quantitative reconstructions and a thorough evaluation and validation of the reconstructed temperatures is indispensable.

In Chapter 5, the lack of specific ecological information about many subfossil chironomid taxa becomes evident. The knowledge about the ecology is limited by the taxonomical resolution of subfossil chironomid taxa and the often 'narrative' character of the ecological information available for chironomids (e.g. Brundin 1949, Wiederholm 1983). Experimental studies about the ecology of chironomid taxa, as exemplified by the study of Brodersen *et al.* (2004), are needed to fully understand the relations between the aquatic fauna and its environment. If these relations are better understood, it will be possible to limit the number of factors potentially influencing the chironomid-assemblages under given conditions, enabling the scientists to select the study sites and the necessary sediment proxies to reconstruct those influencing local factors more precisely.

Chironomid-based quantitative temperature reconstructions are a powerful tool to infer palaeotemperatures as it has already been suggested by Battarbee in the year 2000 (Battarbee 2000). Since then, many studies were carried out to solve the open questions and overcome the difficulties that became apparent during the application of this method (e.g. Brodersen and Anderson 2002, Heiri *et al.* 2003a, Larocque and Hall 2003, Quinlan and Smol 2001, Rieradevall and Brooks 2001). The present study contributes to the knowledge about site-selection for studies which intend to establish chironomid-based Holocene palaeotemperature reconstructions. With the knowledge about the anthropogenic impact on the present climate change as it has been presented lately by the first approved part of the IPCC Synthesis Report 2007 (IPCC 2007), the need for research about past climate change becomes even more urgent than before. By applying and further developing the tool of quantitative chironomid-based temperature reconstructions, palaeolimnologists can contribute an important part to solve such open questions.

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Appendix

The data presented in this thesis can be obtained from the author on request.

	family	Chironomidae				identification follows:											
subfossil chironomid taxa	**subfamily**	**tribe**	**genus**	**remarks**	**abbrevation in modern calibration data**	**Brooks 1997**	**Brooks 2004, in Heiri 2004**	**Cranston 1982**	**Hirvenoja 1973**	**Hofmann 1971**	**Oliver & Roussel 1983**	**Rierdevall 1999**	**Rierdevall & Brooks 2001**	**Saether 1975**	**Schmid 1993**	**Wiederholm 1983**	**Pictures from reference collection**
Chironomus anthracinus-type	Chironominae	Chironomini	Chironomus		Chir ant					42, fig.15							X
Chironomus plumosus-type	Chironominae	Chironomini	Chironomus		Chir plu					42, fig.14							X
Cladopelma lateralis-type	Chironominae	Chironomini	Cladopelma		Cladopel											358	X
Cryptochironomus	Chironominae	Chironomini	Cryptochironomus		Cryptoch											362	X
Demicryptochironomus	Chironominae	Chironomini	Demicryptochironomus		Demicryp											367	X
Dicrotendipes	Chironominae	Chironomini	Dicrotendipes		Dicroten											370	X
Endochironomus albipennis-type	Chironominae	Chironomini	Endochironomus		Endo alb											375	X
Endochironomus dispar-type	Chironominae	Chironomini	Endochironomus		Endo imp											377	X
Lauterborniella	Chironominae	Chironomini	Lauterborniella		Lauterbo											389	X
Microtendipes	Chironominae	Chironomini	Microtendipes		Microten											394	X
Nilothauma	Chironominae	Chironomini	Nilothauma		Nilothau											398	
Omisus	Chironominae	Chironomini	Omisus		Omisus											400	X
Pagastiella	Chironominae	Chironomini	Pagastiella		Pagastie											401	X
Parachironomus	Chironominae	Chironomini	Parachironomus		Parachir											402	X
Paracladopelma	Chironominae	Chironomini	Paracladopelma		Paraclop											403	X
Paratendipes albimanus-type	Chironominae	Chironomini	Paratendipes		Paratend											407	X
Phaenopsectra	Chironominae	Chironomini	Phaenopsectra		Phaenops											409	X
Polypedilum convictum-type	Chironominae	Chironomini	Polypedilum		Poly con											412	X
Polypedilum nubeculosum-type	Chironominae	Chironomini	Polypedilum		Poly nub											410	X
Polypedilum pedestre-type	Chironominae	Chironomini	Polypedilum		Poly ped											411	X
Sergentia	Chironominae	Chironomini	Sergentia		Sergenti					46, fig. 35						420	X
Stenochironomus	Chironominae	Chironomini	Stenochironomus		Stenochi											424	X
Stictochironomus	Chironominae	Chironomini	Stictochironomus		Stictoch											425	X
Tribelos	Chironominae	Chironomini	Tribelos		Tribelos											429	X
Xenochironomus	Chironominae	Chironomini	Xenochironomus		Xenochir											431	X
Chironomini larvula	Chironominae	Chironomini			Chir lar												X
Pseudochironomus	Chironominae	Pseudochironomini	Pseudochironomus		Pseudoch											416	X
Cladotanytarsus mancus-type1	Chironominae	Tanytarsini	Cladotanytarsus		Clad man												X
Cladotanytarsus mancus-type2	Chironominae	Tanytarsini	Cladotanytarsus		Clad spu												X
Micropsectra bidentata-type	Chironominae	Tanytarsini	Micropsectra		Micro bi		X										X
Micropsectra insignilobus-type	Chironominae	Tanytarsini	Micropsectra		Micro in		X										X
Micropsectra radialis-type	Chironominae	Tanytarsini	Micropsectra		Micro ra		X										X
Micropsectra spp.	Chironominae	Tanytarsini	Micropsectra	spur on pedestal present but not assignable to a type	Micro sp												
Paratanytarsus austriacus-type	Chironominae	Tanytarsini	Paratanytarsus		Para aus		X									406	X
Paratanytarsus penicillatus -type	Chironominae	Tanytarsini	Paratanytarsus		Para pen		X										X
Paratanytarsus spp.	Chironominae	Tanytarsini	Paratanytarsus		Paratany												
Rheotanytarsus	Chironominae	Tanytarsini	Rheotanytarsus		Rheotany											417	X
Stempellina	Chironominae	Tanytarsini	Stempellina		Stempell											422	X
Tanytarsus sp. B	Chironominae	Tanytarsini	Tanytarsus		Tanyt B		X										X
Tanytarsus sp. C	Chironominae	Tanytarsini	Tanytarsus		Tanyt C		X			50, fig. 49							X
Tanytarus lugens-type	Chironominae	Tanytarsini	Tanytarsus		Tany lug		X			49, fig. 47							X
Tanytarsus chinyensis-type	Chironominae	Tanytarsini	Tanytarsus	2 or 3 inner teeth on mandible	Tany chi		X			49, fig. 45, 46							X
Tanytarsus pallidicornis-type	Chironominae	Tanytarsini	Tanytarsus		Tany pal		X			50, fig. 48							X
Zavrelia/Stampellinella	Chironominae	Tanytarsini	Zavrelia-Stempellinella		Zavrelia											423/432	X
Tanytarsini indet.	Chironominae	Tanytarsini		not identifiable whether spur on pedestal was present or not	Unid Tan												
Tanytarsini 'no spur'	Chironominae	Tanytarsini		no spur on pedestal	Tany nos												
Diamesa aberrata-type	Diamesinae	Diamesini	Diamesa		Diam abe											127	X
Potthastia	Diamesinae	Diamesini	Potthastia		Potthast											133	
Protanypus	Diamesinae	Protanypini	Protanypus		Protanyp											134	X
Acamptocladius	Orthocladiinae		Acamptocladius		Acamptoc											209	X
Brillia	Orthocladiinae		Brillia		Brillia											213	X
Chaetocladius	Orthocladiinae		Chaetocladius		Chaetocl							X				217	X
Corynoneura coronata-type	Orthocladiinae		Corynoneura	2 middle teeth (mentum)	Cory cor							X					X
Corynoneura lacustris-type	Orthocladiinae		Corynoneura	C. lacustris-type and C. lobata-type ; 3 middle teeth, 1st lateral tooth small (mentum)	Cory lac							X			273	220	X
Corynoneura scutellata-type	Orthocladiinae		Corynoneura	1st lateral tooth equal to other lateral teeth (mentum); reticulations	Cory scu											220	X
Corynoneura spp.	Orthocladiinae		Corynoneura	worn species	Cory sp												

Table A1: Chironomid taxa found in Reiarsdalsvatnet and Isbenttjønn with references used for identification (Brooks et al. 1997, Cranston 1982, Heiri et al. 2004a, Hirvenoja 1973, Hofmann 1971, Oliver and Roussel 1983, Rieradevall 1999, Rieradevall and Brooks 2001, Sæther 1975a, Schmid 1993, Wiederholm 1983). 'Pictures from the reference collection' refers to the collection of S. J. Brooks at the Natural History Museum, London, UK..

	family	Chironomidae				identification follows:											
subfossil chironomid taxa	**subfamily**	**tribe**	**genus**	**remarks**	**abbrevation in modern calibration data**	**Brooks 1997**	**Brooks 2004, in Heiri 2004**	**Cranston 1982**	**Hirvenoja 1973**	**Hofmann 1971**	**Oliver & Roussel 1983**	**Rierdevall 1999**	**Rierdevall & Brooks 2001**	**Saether 1975**	**Schmid 1993**	**Wiederholm 1983**	**Pictures from reference collection**
Cricotopus pulchripes-type	Orthocladiinae		Cricotopus		Cric pul			65, fig. g									X
Cricotopus sp. 285	Orthocladiinae		Cricotopus		Cric 285						213, fig. 285						X
Cricotopus sp. A	Orthocladiinae		Cricotopus		Crico A										287	222, fig. E, F	
Cricotopus sp. B	Orthocladiinae		Cricotopus	C. tremulus-type and Orthocladius oliveri-type	Crico B										299	254, fig. C	
Cricotopus sp. C/D	Orthocladiinae		Cricotopus	C. sp. C and C. sp. D; C. trifascia-type	Crico C						211, fig 277					222, fig. B	X
Cricotopus sylvestris-type	Orthocladiinae		Cricotopus	C. sylvestris-type and C. sp. E	Cric syl				325, fig. 207		212, fig 284				281	222, fig. G	X
Eukiefferiella spp.	Orthocladiinae		Eukiefferiella		Eukieffe										321	229, fig. B	
Eukiefferiella devonica-type	Orthocladiinae		Eukiefferiella	E. ilkleyensis-type and E. devonica-type	Euki ilk										303, 304	229, fig. F	X
Georthocladius/Parachaetocladius	Orthocladiinae		Georthocladius	Georthocladius and Parachaetocladius	Georthoc											234, 256	X
Gymnometriocnemus	Orthocladiinae		Gymnometriocnemus		Bryophae											214, fig. A, 236	X
Heterotanytarsus apicalis-type	Orthocladiinae		Heterotanytarsus		Hete api											239	
Heterotrissocladius grimshawi-type	Orthocladiinae		Heterotrissocladius		Hete gri					40, fig. 8				56, fig. C			X
Heterotrissocladius maeaeri-type	Orthocladiinae		Heterotrissocladius		Hete mae									24		240, fig. D	X
Heterotrissocladius marcidus-type	Orthocladiinae		Heterotrissocladius		Hete mar									35	345	240, fig.E	X
Heterotrissocladius subpilosus-type	Orthocladiinae		Heterotrissocladius		Hete sub									16		240, fig. A	X
Hydrobaenus johannseni-type	Orthocladiinae		Hydrobaenus		Hydr joh											242	X
Hydrobaenus pilosus-type	Orthocladiinae		Hydrobaenus		Hydr pil												X
Limnophyes	Orthocladiinae		Limnophyes		Limnophy										353	245	X
Mesocricotopus	Orthocladiinae		Mesocricotopus		Mesocric											247	X
Metriocnemus hygropetricus-type	Orthocladiinae		Metriocnemus		Metr hyg											249. fig. C	X
Nanocladius rectinervis-type	Orthocladiinae		Nanocladius		Nanoclad											251	
Orthocladius consobrinus-type	Orthocladiinae		Orthocladius		Orth con			107								254, fig., G	X
Orthocladius sp. 3	Orthocladiinae		Orthocladius		Ortho 3												X
Orthocladius sp.	Orthocladiinae		Orthocladius		Orthocla												
Paracricotopus	Orthocladiinae		Paracricotopus		Paracric											258	X
Parakiefferiella bathophila-type	Orthocladiinae		Parakiefferiella		Para bat											259	X
Parakiefferiella finnica-type	Orthocladiinae		Parakiefferiella		Para fen					40, fig. 7							X
Parakiefferiella nigra-type	Orthocladiinae		Parakiefferiella		Para nig	P. sp. A											X
Paraphaenocladius/ Parametriocnemus	Orthocladiinae		Paraphaenocladius	Paraphaenocladius and Parametriocnemus	Paraphae											261, 262	X
Psectrocladius septentrionalis-type	Orthocladiinae		Psectrocladius		Psec sep											268, fig. C, D	X
Psectrocladius sordidellus-type	Orthocladiinae		Psectrocladius		Psec sor											268, fig. E, F	X
Psectrocladius spp.	Orthocladiinae		Psectrocladius		Psec sp												
Psectrocladius (Mesopsectrocladius)	Orthocladiinae		Psectrocladius (Mesopsectrocladius)		Mesopsec											268, fig. B	X
Pseudoorthocladius	Orthocladiinae		Pseudoorthocladius		Pseudort											270	X
Pseudosmittia	Orthocladiinae		Pseudosmittia		Pseudosm											271	
Rheocricotopus	Orthocladiinae		Rheocricotopus		Rheocric			451								273	X
Smittia	Orthocladiinae		Smittia		Smittia			455, 457									X
Symposiocladius	Orthocladiinae		Symposiocladius		Symposio			465								279	
Synorthocladius semivirens-type	Orthocladiinae		Synorthocladius		Synortho			467								280	X
Thienemaniella	Orthocladiinae		Thienemaniella		Thienmal			471, 473, 475								284	
Thienemanniella mt long	Orthocladiinae		Thienemanniella		Thie mtl			483									X
Zalutschia tornetraeskiensis-type	Orthocladiinae		Zalutschia		Zalu lin											291, fig. B	X
Zalutschia zalutschicola-type	Orthocladiinae		Zalutschia		Zalu zal											291, fig. A	X
Orthocladiinae indet.	Orthocladiinae				Orth und												
Parochlus kiefferi-type	Podonominae	Podonomini	Parochlus		Paro kie											30	
Prodiamesa	Prodiamesinae		Prodiamesa		Prodiame											147	X
Macropelopia	Tanypodinae	Macropelopiini	Macropelopia		Macropel								X				
Ablabesmyia	Tanypodinae	Pentaneurini	Ablabesmyia		Ablabesm								X			74	
Conchapelopia	Tanypodinae	Pentaneurini	Conchapelopia		Conchape								X				
Guttipelopia	Tanypodinae	Pentaneurini	Guttipelopia		Guttipel								X				
Krenopelopia	Tanypodinae	Pentaneurini	Krenopelopia		Krenopel								X				
Labrundinia	Tanypodinae	Pentaneurini	Labrundinia		Labrundi								X				
Nilotanypus	Tanypodinae	Pentaneurini	Nilotanypus		Nilotany								X				
Paramerina	Tanypodinae	Pentaneurini	Paramerina		Parameri								X				
Thienemannimyia	Tanypodinae	Pentaneurini	Thienemannimyia		Thienmia								X				
Xenopelopia	Tanypodinae	Pentaneurini	Xenopelopia		Xenopelo								X				
Zavrelimyia	Tanypodinae	Pentaneurini	Zavrelimyia		Zavrelim								X				
Pentaneurini genus 1	Tanypodinae	Pentaneurini			Penta 1												X
Pentaneurini genus 4	Tanypodinae	Pentaneurini			Penta 4												
Procladius	Tanypodinae	Procladiini	Procladius		Procladi								X			100	
Pentaneurini ndet.	Tanypodinae		Tanypodiinae		Unid Pen												

Table A1: - continued -

		Saether 1979				Moog 2002					composite Lüder 2006			
subfossil chironomid taxa	Species identified in southern Norway (Limnofauna Norvegica 1996)	oligo-trophic	meso-trophic	eutro-phic	humic	feeding group det: collector-gatherer räu: predator wei: scraper afil: collector-filterer zkl: shredder min: piercer (plants) hol: shrederer (wood)	habitat preference 1: lotic 2: lentic littoral 3: lentic profundal	absolute number littoral	absolute number profundal	remarks from Moog 2002	trophy 1: oligotrophic 2: mesotrophic 3: eutrophic	humicity	habitat preference 1: lotic 2: lentic littoral 3: lentic profundal	feeding group det: collector-gatherer räu: predator wei: scraper afil: collector-filterer zkl: shredder min: piercer (plants) hol: shrederer (wood)
Chironomus anthracinus-type	C. anthracinus			1		det	3	2	8		**3**		**3**	**det**
Chironomus plumosus-type	C. plumosus			1		det	3	3	4		**3**		**3**	**det**
Cladopelma lateralis-type	--										**2**	**1**	**2**	**det**
	C. bicarinata													
	C. virescens					det	2	7	0					
	C. viridula		1		1	det	2	6	1					
Cryptochironomus													**2**	**räu**
	C. psittacinus						2	9	1					
	C. rostatus					räu	1	1	0					
	C. supplicans					räu	2	9	1					
Demicryptochironomus											**3**	**1**	**2**	**det, räu**
	D. vulneratus			1	1	det. räu	2	6	1					
Dicrotendipes											**3**	**1**	**2**	**wei**
	D. lobiger					wei	2	10	0					
	D. modestus					det	2	9	1					
	D. nervosus			1	1	wei	1	3	0					
	D. tritomus					wei	2	10	0					
Endochironomus albipennis-type	--			1	1	afil	2	7	0		**3**	**1**	**2**	**afil**
Endochironomus dispar-type	E. dispar					afil	2	7	0				**2**	**afil**
Lauterborniella													**2**	
	L. agrailoides						2	10	0					
Microtendipes													**2**	**det**
	M. brevitaris													
	M. chloris					det	2	6	0					
	M. pedellus					det	1,2	5	0					
	M. ryalensis													
Nilothauma	--													
Omisus														
	O. caledonicus													
Pagastiella											**1**	**1**	**2**	
	P. orophila	1			1		2	8	2					
Parachironomus													**2**	**wei, räu**
	P. arcuatus					wei, det	2	6	0					
	P. digitalis													
	P. tenuicaudatus					räu	2	10	0					
	P. vitiosus					wei	2	7	0					
Paracladopelma											**1**		**2,3**	**det**
	P. laminata						2	7	0					
	P. nigritula	1				det	3	1	7					
	P. undine	1												
Paratendipes albimanus-type	P. albimanus					det	1	3	1				**2**	**det**
Phaenopsectra													**2**	**wei, det**
	P. flavipes					wei, det	1	4	0					
	P. punctipes					wei, det								
Polypedilum convictum-type	P. convictum						1	0	0				**1**	
Polypedilum nubeculosum-type	P. nubeculosum			1		det	1	2	1		**3**		**1**	**det**
Polypedilum pedestre-type	P. pedestre					det	1	1	0				**1**	**det**
Sergentia	S. coracina	1				det	3	2	8		**1**		**3**	**det**
Stenochironomus														
	S. fascipennis													
Stictochironomus											**1**		**2,3**	**det**
	S. histrio													
	S. maculipennis													
	S. pictulus													
	S. rosenschoeldi	1					3	2	8					
	S. sticiticus					det	2	8	0					
Tribelos													**2**	**det**
	T. intextus					det	2	10	0					

Table A2: Compilation of chironomid species possibly included in subfossil chironomid taxa according to Schnell and Aargaard (1996), and their trophic, habitat and feeding habits according to Sæther (1979) and Moog (2002).

		Saether 1979				Moog 2002					composite Lüder 2006			
subfossil chironomid taxa	Species identified in southern Norway (Limnofauna Norvegica 1996)	oligo-trophic	meso-trophic	eutro-phic	humic	feeding group det: collector-gatherer räu: predator wei: scraper afil: collector-filterer zkl: shredder min: piercer (plants) hol: shrederer (wood)	habitat preference 1: lotic 2: lentic littoral 3: lentic profundal	absolute number littoral	absolute number profundal	remarks from Moog 2002	trophy 1: oligotrophic 2: mesotrophic 3: eutrophic	humicity	habitat preference 1: lotic 2: lentic littoral 3: lentic profundal	feeding group det: collector-gatherer räu: predator wei: scraper afil: collector-filterer zkl: shredder min: piercer (plants) hol: shrederer (wood)
Xenochironomus													**2**	**par**
	X. xenolabis					par	2	7	0					
Chironomini larvula														
Pseudochironomus													**2**	**det**
	P. prasinatus					det	2	10	0					
Cladotanytarsus mancus-type1	C. mancus					wet, afil	1,2	5	0				**2**	**wei, afil**
Cladotanytarsus mancus-type2	C. mancus					wei, afil	1,2	5	0				**2**	**wei, afil**
Micropsectra bidentata-type	M. bidentata													
Micropsectra insignilobus-type											**1**		**3**	**det**
	M. atrofasciata					det	1	1	0					
	M. contracta	1				det	3	2	8					
	M. groenlandica	1				det	3	2	8					
	M. insignilobis	1												
	M. junci					det	1	1	0					
Micropsectra radialis-type	M. radialis					det	3	2	8				**3**	**det**
Micropsectra spp.														
Paratanytarsus austriacus-type	P. austriacus					wei	1	3	1				**1**	**wei**
Paratanytarsus penicillatus -type	P. penicillatus	1			1		2	10	0		**1**	**1**	**2**	
Paratanytarsus spp.														
Rheotanytarsus													**1**	
	R. distinctissimus						1							
	R. muscicola						1							
	R. pentapoda						1							
	R. ringei						1							
Stempellina											**1**	**1**	**2**	
	S. bausei	1			1		2	5	1					
Tanytarsus sp. B											**2**		**2,3**	
	T. ejucindus					det	1	4	0					
	T. gregarius		1				3	2	8					
	T. inaequalis		1				3	2	8					
	T. lestagei		1				2	10	0					
	T. medius													
	T. mendax													
	T. striatulus													
Tanytarsus sp. C														
Tanytarus lugens-type											**1**		**2,3**	
	T. bathophilus	1					3	2	8					
	T. gracilentus						2	9	1					
	T. lugens	1												
Tanytarsus chinyensis-type	T. brundini					det	1	4	0				**1**	**det**
Tanytarsus pallidicornis-type											**3**		**1,2**	**det**
	T. buchonius													
	T. pallidicornis					det	1	4	0					
	T. usmaensis			1			2	10	0					
Zavrelia/Stampellinella											**1**		**2**	
	S. brevis	1					2	6	0					
	S. minor	1					1,2	5	0					
	Z. pentatoma						2	9	0					
Tanytarsini indet.														
Tanytarsini 'no spur'														
Diamesa aberrata-type	D. aberrata					wei	1	0	0				**1**	**wei**
Potthastia													**1**	**det, wei**
	P. gaedii					wei								
	P. longimana					det	1							
Protanypus											**1**	**1**	**3**	**räu**
	P. caudatus	1					3	0	10					
	P. morio	1			1	räu	3	0	10					
Acamptocladius														
	A. reissi													
	A. submontanus													
Brillia													**1**	**zkl**
	B. longifurca													
	B. modesta					zkl	1	1	0					

Table A2: - continued -

		Saether 1979				Moog 2002					composite Lüder 2006			
subfossil chironomid taxa	Species identified in southern Norway (Limnofauna Norvegica 1996)	oligo-trophic	meso-trophic	eutro-phic	humic	feeding group det: collector-gatherer räu: predator wei: scraper afil: collector-filterer zkl: shredder min: piercer (plants) hol: shrederer (wood)	habitat preference 1: lotic 2: lentic littoral 3: lentic profundal	absolute number littoral	absolute number profundal	remarks from Moog 2002	trophy 1: oligotrophic 2: mesotrophic 3: eutrophic	humicity	habitat preference 1: lotic 2: lentic littoral 3: lentic profundal	feeding group det: collector-gatherer räu: predator wei: scraper afil: collector-filterer zkl: shredder min: piercer (plants) hol: shrederer (wood)
Chaetocladius														**det**
	C. acuminatus													
	C. dissipatus					det				shallow waters				
	C. gelidus					det				shallow waters				
	C. laminatus					det				shallow waters				
	C. perennis					det				shallow waters				
	C. suecicus													
Corynoneura coronata-type	--													
Corynoneura lacustris-type	C. lacustris					wei							**1**	**wei**
	C. lobata					wei	1	0	0					
Corynoneura scutellata-type	C. edwardsi												**2**	**wei**
	C. scutellata					wei	2	10	0					
Corynoneura spp.						wei								**wei**
Cricotopus pulchripes-type	C. pulchripes													
Cricotopus sp. 285														
Cricotopus sp. A	C. bicinctus													
	C. cylandraceus													
Cricotopus sp. B														
Cricotopus sp. C/D														
Cricotopus sylvestris-type											**3**	**1**	**2**	
	C. sylvestris			1	1		1,2	5	0					
	C. laricomalis						2	10	0					
Eukiefferiella spp.	E. claripennis					wei	1	1	0				**1**	**wei**
Eukiefferiella devonica-type	E. devonica					wei	1	0	0				**1**	**wei**
Georthocladius/Parachaetocladius	G. luteicornis									Sphagnum in mires				
Gymnometriocnemus														
	B. faegrii													
	B. ictericus													
	B. inconstans													
	B. nitidicollis													
	B. subvernalis									semiaquatic				
	G. brumalis									terrestric				
	G. volitans													
Heterotanytarsus apicalis-type	H. apicalis	1			1	det	1	0	0		**1**	**1**	**1**	**det**
Heterotrissocladius grimshawi-type	H. grimshawi	1									**1**			
Heterotrissocladius maeaeri-type	H. maeaeri	1									**1**			
Heterotrissocladius marcidus-type	H. marcidus	1			1	det	1	3	1		**1**	**1**	**1**	**det**
Heterotrissocladius subpilosus-type	H. subpilosus	1									**1**			
Hydrobaenus johannseni-type	--													
Hydrobaenus pilosus-type	--													
Limnophyes													**2**	
	L. asquamatus						2	10	0					
	L. bidumus													
	L. brachytomus													
	L. difficilis													
	L. edwardsi													
	L. er													
	L. habilis													
	L. minimus						2	8	0	semiaquatic				
	L. natalensis													
	L. ninae													
	L. pumilio													
	L. schnelli													
	L. spinigus													
Mesocricotopus											**1**			
	M. thienemanni	1												
Metriocnemus hygropetricus-type	--													
Nanocladius rectinervis-type											**1**	**1**	**1,2**	**det**
	N. rectinervis	1			1	det	1	1	0					
Orthocladius consobrinus-type	O. consobrinus	1					2	9	1	standing waters	**1**		**2**	
Orthocladius sp. 3														
Orthocladius spp.	Orthocladius													
Paracricotopus													**1**	**wei**
	P. niger					wei	1	0	0					
Parakiefferiella bathophila-type	P. bathophila					det	1	4	1				**2**	**det**
Parakiefferiella finnica-type	P. fennica													
Parakiefferiella nigra-type	P. nigra					det								**det**

Table A2: - continued -

		Saether 1979				Moog 2002					composite Lüder 2006			
subfossil chironomid taxa	Species identified in southern Norway (Limnofauna Norvegica 1996)	oligo-trophic	meso-trophic	eutro-phic	humic	feeding group det: collector-gatherer räu: predator wei: scraper afil: collector-filterer zkl: shredder min: piercer (plants) hol: shrederer (wood)	habitat preference 1: lotic 2: lentic littoral 3: lentic profundal	absolute number littoral	absolute number profundal	remarks from Moog 2002	trophy 1: oligotrophic 2: mesotrophic 3: eutrophic	humicity	habitat preference 1: lotic 2: lentic littoral 3: lentic profundal	feeding group det: collector-gatherer räu: predator wei: scraper afil: collector-filterer zkl: shredder min: piercer (plants) hol: shrederer (wood)
Paraphaenocladius/ Parametriocnemus													**1**	
	P. preudirritus						1	2	0					
Psectrocladius septentrionalis-type	P. septentrionalis													
Psectrocladius sordidellus-type	P. sordidellus						2	6	1				**2**	
Psectrocladius spp.										waters in mires				
Psectrocladius (Mesopsectrocladius)	P. barbartipes													
Pseudorthocladius													**2**	
	P. filiformis						1,2	5	0	shallow waters, semiaquatic				
	P. macrovirgatus													
	P. rectangilobus													
Pseudosmittia													**2**	
	P. oxoniana													
	P. recta													
	P. ruttneri						2	10	0					
	P. trilobata									semiterrestric				
Rheocricotopus													**1**	**det**
	R. effusus					det	1	0	0					
	R. fuscipes					det	1	0	0					
Smittia														
	S. aterrima													
	S. leucopogon									semiterrestric				
	S nudipennis													
Symposiocladius													**1**	**hol**
	S. lignicola					hol	1	0	0					
Synorthocladius semivirens-type													**1**	**wei, det**
	S. semivirens					wei, det	1	2	0					
Thienemaniella	--					wei	1	0	0				**1**	**wei**
Thienemanniella mt long	--					wei	1	0	0				**1**	**wei**
Zalutschia tornetraeskiensis-type	Z. torntraeskensis	1									**1**			
Zalutschia zalutschicola-type	Z. zalutschicola	1			1						**1**	**1**		
Orthocladiinae indet.						det, wei								
Parochlus kiefferi-type	P. kiefferi					det	1	0	0				**1**	**det**
Prodiamesa													**1**	**det**
	P. olivacea					det	1							
Macropelopia													**1**	**räu**
	M. adaucta													
	M. nebulosa					räu	1	2	1					
Ablabesmyia													**1,2**	**räu**
	A. longistyla					räu	1							
	A. monilis					räu								
	A. phatta					räu	2	8	1					
Conchapelopia													**1**	**räu**
	C. intermedia													
	C. melanops					räu	1	2	0					
	C. pallidula					räu	1	0	0					
Guttipelopia														
	G. guttipennis													
Krenopelopia													**1**	**räu**
	K. binotata					räu	1	1	0					
Labrundinia	--													
Nilotanypus													**1**	**räu**
	N. dubius					räu	1	2	0					
Paramerina													**1**	**räu**
	P. cingulata					räu	1	2	0					
Thienemannimyia											**1**		**1**	**räu**
	T. carnea					räu	1	1	0					
	T. fusciceps	1				räu								
	T. pseudocarnea					räu								
Xenopelopia													**2**	**räu**
	X. nigricans					räu	2	10	0					
Zavrelimyia													**1,2**	**räu**
	Z. barbatipes					räu	1	1	0					
	Z. hirtimana					räu	2	10	0					
	Z. melanura					räu	1	1	0					
	cfr. Z. thryptica					räu								
Pentaneurini genus 1														

Table A2: - continued -

		Saether 1979				Moog 2002					composite Lüder 2006			
subfossil chironomid taxa	Species identified in southern Norway (Limnofauna Norvegica 1996)	oligo-trophic	meso-trophic	eutro-phic	humic	feeding group det: collector-gatherer räu: predator wei: scraper afil: collector-filterer zkl: shredder min: piercer (plants) hol: shrederer (wood)	habitat preference 1: lotic 2: lentic littoral 3: lentic profundal	absolute number littoral	absolute number profundal	remarks from Moog 2002	trophy 1: oligotrophic 2: mesotrophic 3: eutrophic	humicity	habitat preference 1: lotic 2: lentic littoral 3: lentic profundal	feeding group det: collector-gatherer räu: predator wei: scraper afil: collector-filterer zkl: shredder min: piercer (plants) hol: shrederer (wood)
Pentaneurini genus 4														
Procladius													2	räu
	P. appropinquatus													
	P. barbatus													
	P. choreus					räu	2	5	2					
	P. cinereus													
	P. signatus					räu								
	P. simplicistylis													
Pentaneurini indet.														

Table A2: - continued -

					Categorised as 'less reliable' because of ...		
	Lake	Code	Depth [cm]	Age [cal. BP]	< 50 hc	Numerical evaluation criteria	Site-specific validation
Pollen	**RV**	892	58	624.639			X
		896	62	676.769			X
		900	66	730.108			X
		904	70	784.745			X
		908	74	840.779			X
		912	78	898.308			X
		916	82	957.43			X
		920	86	1018.24			X
		924	90	1080.85			X
		976	40	1283.01		X	
		1100	266	6558.46		X	
		1104	270	6751.14		X	
		1108	274	6945.1		X	
		1112	278	7140.29		X	
		1116	282	7336.66		X	
		1120	286	7534.16		X	
		1136	302	8334.53		X	
		1156	322	9354.59		X	
		1158	324	9457.55		X	
		1160	326	9560.63		X	
		1162	328	9663.81		X	
		1166	332	9870.36		X	
		1176	342	10387.1		X	
		1178	344	10490.4		X	
	IT	1126	190	7762.35		X	
		1130	194	8006.82		X	
		1146	210	9010.74		X	
		1152	216	9392.68		X	
Chironomids	**RV**	1166	332	9870	X		
		1170	336	10077	X		
		1172	338	10180	X		
	IT	936	0	-45			X
		940	4	87			X
		944	8	219			X
		948	12	351			X
		952	16	483			X
		956	20	616			X
		960	24	748			X
		964	28	881			X
		968	32	1015			X
		972	36	1149			X
		976	40	1283			X
		1038	102	3479	X		
		1054	118	4108	X		
		1066	130	4613			
		1148	212	9138		X	
		1152	216	9393	X		

Table A3: Pollen and chironomid samples of Reiarsdalsvatnet (RV) and Isbenttjønn (IT) with inferred temperatures categorised as 'less reliable'. Samples with less than 50 chironomid head capsules (hc) were excluded before the temperatures were reconstructed.

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