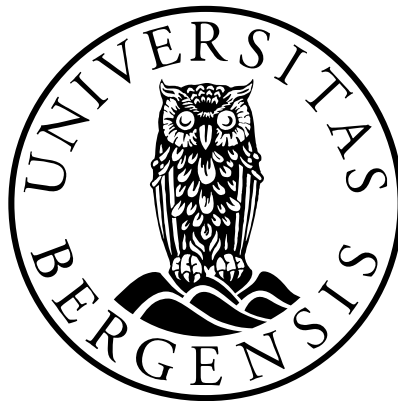


Continuous and episodic sedimentation in western Norwegian fjord lakes

A Holocene climatic perspective

Kristian Vasskog



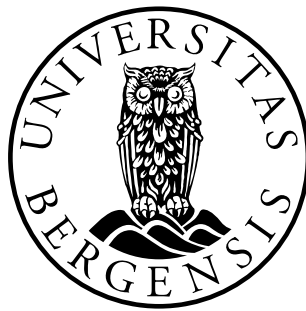
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Scientific environment

This dissertation is the result of research conducted at the Bjerknes Centre for Climate Research (BCCR) through a 4-year scholarship granted from the Department of Earth Science at the University of Bergen (UoB), Norway. The work was funded through the UoB scholarship and the “NORLAKE” project, an internal BCCR project led by Professor Atle Nesje.



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Bergen, 10. June, 2011

Kristian Vasskog

Abstract

A Holocene chronology of hazardous events has been constructed in parallel with a new record of glacier variability from inner Nordfjord in western Norway, based on the analysis of seismic profiles and sediment cores from the lakes Oldevatnet (8 km²), Nerfloen (1 km²) and Oppstrynsvatnet (30 km²).

In paper I the frequency of episodic sedimentation events over the last 7300 years was investigated in a sediment core retrieved from Oldevatnet in inner Nordfjord, western Norway. Our data suggest that the event record is dominated by snow-avalanches, whereas inferred floods and density currents are too infrequent to be of any palaeoclimatic significance. Altogether forty-seven snow-avalanche events are recorded over the investigated interval. Periods of enhanced snow-avalanche activity are recorded at 5500–5400, 5000–4900, 1200–1100 cal. yr BP and during the ‘Little Ice Age’ (LIA) glacier maximum (*c.* 400–100 cal. yr BP). Periods without any large snow-avalanches entering the lake are seen between 7100–5700, 4200–3700, 3200–2800, and 1400–1300 cal. yr BP. A compilation of snow-avalanche records from western Norway reflect an increasing trend through the Holocene, similar to what is seen in records of other types of extreme events such as floods. It seems likely that regional changes in winter precipitation are crucial for the fluctuations observed in snow-avalanche activity, although local effects may give rise to site-specific responses. Around Oldevatnet, the glacier expansion during the LIA probably served to increase the local snow-avalanche activity as the glacier fronts expanded into the steep slopes surrounding the lake.

In paper II a Principal Component Analysis (PCA) was applied to a suite of different sedimentary parameters with the purpose of reconstructing past glacier activity in the 440 km² upstream catchment of lake Nerfloen in Stryn, western Norway. The PCA reveals a strong signal contained in the sediment record, and is able to express 76% of the total variability of the fifteen investigated parameters through the first principal component. Changes in grain-size distribution is seen as the main driver of the sedimentary signal, and a comparison with known glacier fluctuations in the area indicate that it is closely connected with glacier extent in the upstream catchment. This interpretation was supported by measurements of bulk magnetic susceptibility (χ_{Bulk}) of glacial and non-glacial sediment

samples from the catchment, which for relevant grain-size fractions could be directly correlated with χ_{Bulk} values in the core. The ratio between χ_{Bulk} measured at temperatures of 77K and 293K show a high sensitivity to changes between sedimentation regimes dominated by glacial and non-glacial sedimentation in the lake. By combining the 77K/293K-ratio with the PCA, periods of significant glacier retreat can be robustly determined. In the ~8000 year long record, only minor glacial input is indicated between 6700-5700 cal. yr BP, probably reflecting a situation when most glaciers in the catchment had melted away, whereas the highest glacier activity is observed around 600 and 200 cal. yr BP. During the local Neoglacial interval (after ~4200 cal. yr BP) five individual periods of significant glacier retreat are identified at ~3400, 3000-2700, 2100-2000, 1700-1500 and ~900 cal. yr BP.

Paper III deals with the Storegga tsunami, which has evidently caused the most significant episodic sedimentation event recorded in Nerfloen and adjacent Oppstrynsvatnet (29 m a.s.l.). Triggered by the ~3500 km³ Storegga Slide that occurred off the coast of Norway at around 8100 cal. yr BP, this catastrophic tsunami inundated coastal areas around the North Atlantic, and numerical simulations have suggested that the tsunami wave propagated into the fjords of western Norway with a considerable amplification towards the fjord heads. This is, however, the first time that actual geologic evidence of the tsunami has been discovered at the head of a major fjord in western Norway, and the first finding of Storegga tsunami deposits within the Nordfjord system. The impact of the tsunami can be seen as a distinct erosive boundary in Nerfloen and the shallow parts of Oppstrynsvatnet, whereas in the main Oppstrynsvatnet basin an up to 2.5 m thick ‘rapidly deposited layer’ (RDL) has been deposited across an area of 5 km². In the sediment core from Nerfloen, the event is reflected by a 15 cm thick turbidite deposit overlain by a 5 cm thick unit consisting of terrestrial debris. Although the exact run-up of the Storegga tsunami in Stryn cannot be determined from our data, the magnitude of the observed erosion and deposition related to the event suggest that the impact involved massive amounts of energy. By verifying to some extent the numerical simulations that has been performed of the Storegga tsunami, these results underline how vulnerable fjord areas are to tsunamis generated in the open ocean.

List of papers

Paper I:

Vasskog, K., Nesje, A., Støren, E. N., Waldmann, N., Chapron, E., and Ariztegui, D., 2011, A Holocene record of snow-avalanche and flood activity reconstructed from a lacustrine sedimentary sequence in Oldevatnet, western Norway: *The Holocene* 21, 597-614

Paper II:

Vasskog, K., Paasche, Ø., Nesje, A., Boyle, J. F. and Birks, H.J.B., Building continuous glacier reconstructions based on the integrated sedimentary response of large catchments, Submitted to *Quaternary Research*, February 28, 2011

Paper III:

Vasskog, K., Waldmann, N., Nesje, A., Chapron, E. and Ariztegui, D., New insight into the 8100 cal yr BP catastrophic Storegga tsunami event from western Norway, Manuscript in preparation

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Outline

This thesis consists of an introduction and three individual papers. A common goal for the three papers has been to identify the different ‘fingerprints’ of continuous and episodic sedimentation, and to understand the associated processes and their relative contribution in the postglacial sedimentation of Oldevatnet, Oppstrynsvatnet and Nerfloen, three fjord lakes situated in inner Nordfjord, western Norway. Paper I presents a new record of snow-avalanche activity spanning the last 7300 years obtained from Oldevatnet. This was accomplished by investigating seismic profiles and sediment cores along a one-kilometre transect in the lake, allowing episodic sedimentation events to be recognised and distinguished from the glacially dominated continuous sedimentation. Paper II complements the results of paper I by shifting the focus to the continuous sedimentation in Nerfloen. Here, a numerical analysis of multiple sedimentary parameters from the lake core was combined with analyses of catchment samples, in order to assess the varying contribution from glaciers to the continuous lake sedimentation. Paper III provides evidence that the Storegga tsunami reached inner Nordfjord, thereby supporting numerical models that suggest a larger impact than what has been known from geological evidence. The tsunami is the single most significant episodic sedimentation event recorded in the investigated basins.

Seen together the three papers provide a detailed overview of the interaction between different sedimentary processes in western Norwegian fjord lakes, which range from the continuous supply of glacial and non-glacial material from the lake catchment, via the rapid sedimentation connected to floods and sub-aerial mass-movement, to the unique Storegga tsunami event.

The introduction will provide an overview of the scientific background for the papers and discuss results from paper I and II in a palaeoclimatic context.

Introduction

Lakes are able to store information about past and present environmental change, a quality that makes them highly valued. Throughout the past decades a vast number of lake sediment studies have been conducted with the purpose of reconstructing past environmental and climate change. A range of different methods can be used to retrieve the information embedded in lacustrine sediments. For instance, assemblages of diatoms or other microscopic algae allow for reconstructing past lake-water conditions such as temperature, salinity and/or pH (e.g. Jankovská and Komárek, 2000; Battarbee et al., 2002); the study of insect remains or pollen can be used to infer past summer temperatures on a local to regional scale (e.g. Velle et al., 2005; Bjune et al., 2005); whereas physical, sedimentological and geochemical properties of the lake sediment provide information about past sedimentary processes in the catchment such as glacier activity (e.g. Karlén, 1976; 1981; Leemann and Niessen, 1994; Leonard and Reasoner, 1999; Nesje et al., 2001; Paasche et al., 2007; Bakke et al., 2010).

Common to most lake studies with a palaeoclimatic perspective is the focus on climate-driven changes in the continuous sedimentation, whereas episodic sedimentation is commonly viewed as a potential source of noise (e.g. Rubensdotter, 2006). Contrary to this view, Støren et al. (2010) successfully demonstrated that episodic sedimentation may also provide important information about past climate. Here we provide additional evidence that episodic sedimentation events can be equally valuable for reconstructions of past environmental processes – a central theme in papers I-III. For instance, in paper II we map and explain the influence of glacier activity on continuously deposited lake sediments, and we point out that the identification of episodic sedimentation is crucial for avoiding erroneous interpretations (cf. Rubensdotter, 2006). Seismic profiling and bathymetric surveys may also provide invaluable information in this respect, as demonstrated by the unique sedimentary imprint of the Storegga tsunami (paper III) which could not have been mapped in its entirety from sediment cores alone.

In western Norway, but also elsewhere, common processes that are able to trigger episodic sedimentation include floods and mass-wasting events such as debris-flows, snow-avalanches and rock falls. Because such events are often triggered by extreme weather

situations, records of episodic sedimentation have the potential to shed light on the variability of extreme weather events in the past, providing data that is not readily available from other palaeoclimatic archives. Linking records of extreme weather events with climate is, however, not straightforward because 1) the relationship between long-term climate change and the frequency and magnitude of extreme weather events are generally poorly understood (e.g. Hegerl et al., 2011); 2) reliable millennial-scale reconstructions of extreme events are scarce, and 3) local conditions may give rise to site-specific anomalies in extreme event records. Climatic variables such as precipitation and temperature provide certain boundary conditions for the type and frequency of geohazards that may occur in a given area, and a change in these variables over time is therefore expected to induce a response in geohazard frequency. However, the relationship may well be non-linear and subject to threshold-related responses (McCarroll and Matthews, 1997). Furthermore, truly extreme events usually result from an unlikely combination of unfortunate circumstances (cf. the ‘Stor-Ofsen’ event of 1789; Østmoe, 1985), which introduce a stochastic element in the occurrence of extreme events. The climatic influence on any extreme event record is therefore expected to be somewhat disturbed by noise. One approach is to combine several records from the same area or climatic region, in which case the ‘noise’ represented by stochastic and site-specific influences should -in theory- be reduced. This approach was explored to some extent in paper I.

Study area

The investigated lakes Oldevatnet and Oppstrynsvatnet/Nerfloen are ‘fjord lakes’ in the strictest definition of the term (Figure 1). Having formed in elongated glacially eroded troughs and dammed by bedrock sills, they share morphology with the fjords of western Norway.

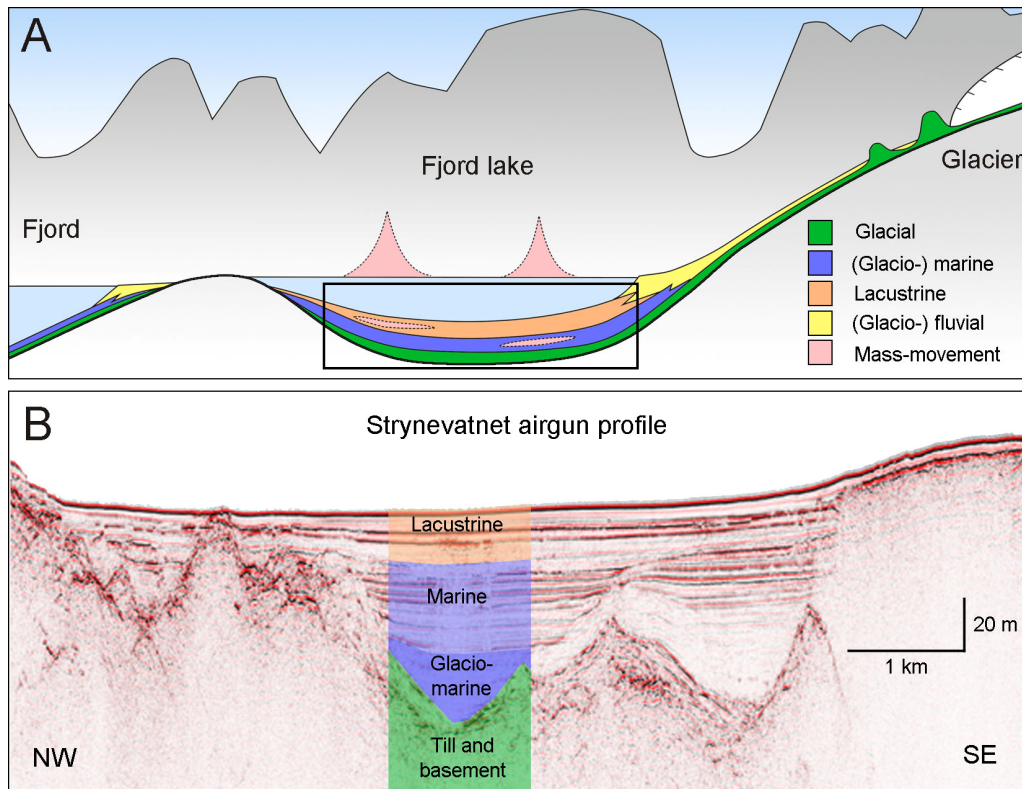


Figure 1: A) Schematic profile from the Jostedalsbreen glacier (right) to the Nordfjord (left) running through a lacustrine basin featuring an infill succession that is typical for the investigated fjord lakes (figure modified from <http://www.ngu.no/seditrans/>). B) 1 inch³ airgun profile from the deepest part of Oppstrynsvatnet (water depth ~200 m) showing how the infill sequence is reflected in seismic profiles. Note how the postglacial infill drapes the undulating basement and till, creating an almost entirely flat lake bottom topography.

Following deglaciation some 11,000 years ago, the lakes were themselves part of the fjord system and subjected to glaciomarine and marine sedimentation for about two thousand years (paper III). After being isolated from the sea due to glacio-isostatic uplift, the lakes have acted as effective ‘sediment traps’ in what may be described as a source-to-sink system running from the Jostedalsbreen glacier to the Nordfjord (Figure 1). Consequently only fine-grained sediments are able to travel in suspension through the large lakes and make it into

the fjord, typically clay and fine silt, whereas coarser material is deposited within them. Apart from the sediment derived from direct glacier erosion, the formerly glaciated areas within the lake catchments feature a variety of unconsolidated sediment such as marine- and (glacio-) fluvial sediments, slope deposits and till, which all contribute to the sedimentary budget of the investigated lakes (Figure 2)

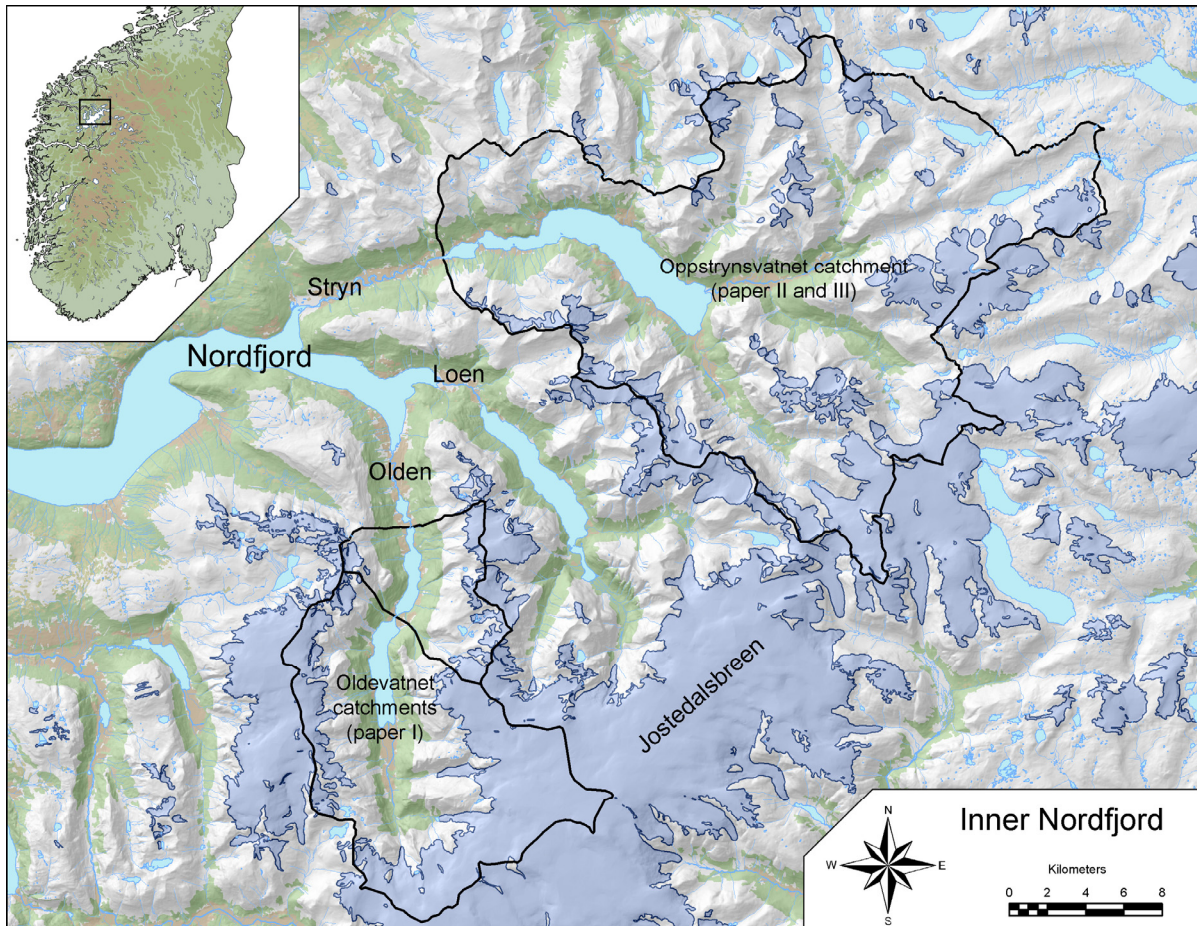


Figure 2: Map of the field area with the catchment areas of the investigated lakes marked. Inset map of southern Norway shows the location of the field area (square).

Paper I: Extreme events

Snow-avalanches, floods, and debris-flows are all geohazards of high societal significance, and there is currently a need to increase our understanding of interactions between climate and different types of geohazards in order to properly assess the full impact of future climate change on human society. Over the last year (2010-2011) floods and debris-flows have affected millions of people worldwide, and the influence of recent climate change on the frequency of such events have been discussed (e.g. Min et al., 2011; Webster et al., 2011). Historically, snow-avalanche activity represents the deadliest geohazard in Norway, and the number of snow-avalanche casualties during the winter of 2010-2011 was the highest over the last 25 years (www.snoskred.no).

In the historical record we find that certain periods and areas have been more frequently affected by extreme events than others. This is reflected in the writings of Martinus E. Bødal, who describes some of the challenges faced by farmers in inner Nordfjord during the period known as the ‘Little Ice Age’ (LIA):

“Aar 1743 den 12te decbr. atter stor skade på Tungøen ved udrasing af bræen, som bortrev hus med indbo, folk, kreaturer, stort og smaat. Kun en tjenestedreng og en 12 aars gammel gut samt to kjør reddedes. Aar 1744 var der skifte efter Gullak Tungøen og kone, og der fantes kun de to reddede kjør, en fjærpute, to veste og en gammel sæk.”

“12. December, 1743. The Tungøen farm has again been greatly damaged by an avalanche from the glacier, which tore away houses, people and animals, large and small. The only survivors were a servant, a 12 year old boy and two cows. In 1744 the heritage of Gullak Tungøen and his wife was divided, and consisted only of the two rescued cows, a feather pillow, two waistcoats and an old sack.”

From Nesje and Aa (1989) citing Rekstad (1902)

In the period between AD 1667 and 1768 an exceptional fall in the tax known as ‘landskyld’, occurred in inner Nordfjord, whereas it remained relatively stable in many neighbouring areas (Grove, 1972). The landskyld was an annual tax that farmers had to pay the owner of their land (usually the king) and was calculated after an official assessment of each farm. A Royal decree of AD 1655 revised the landskyld assessment to include hazards

of flooding and landslides, which resulted in a detailed record of all events that caused damage to farms or farmland. Based on the landskyld records, Grove (1972) concludes that there was a period of significantly higher frequency of hazardous events in inner Nordfjord between AD 1650 and 1760. The purpose of the study presented in paper I was to expand the record of hazardous events beyond the limit of historical sources using lake sediments.

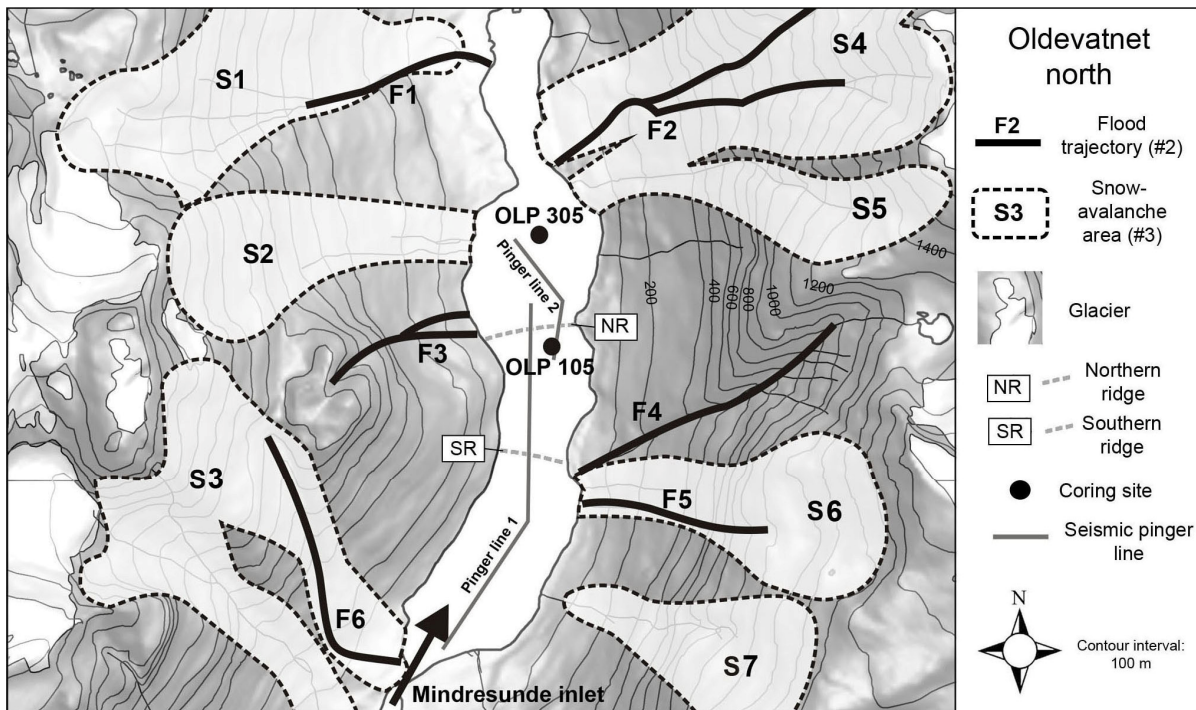


Figure 3: Map of the northern Oldevatnet basin studied in paper I. Note that the Oldevatnet snow-avalanche record is reconstructed from the distal OLP 105 core. In addition to being located at maximum distance from any colluvial fan it is also ‘protected’ by two sub-aquatic ridges (probably recessional moraines).

A prerequisite for studying episodic sedimentation in a lake is the ability to distinguish it from the continuous lacustrine sedimentation (e.g. Støren et al., 2008). The distinction between continuous and episodic sedimentation may not always be very clear, particularly not in proglacial hydrological systems where the bulk of annual sediment transport may occur within a few single days of high glacier melt and resulting extreme discharge (Østrem, 1975). In the Oldevatnet watershed, discharge is very sensitive to glacier melt and consequently display annual-, and during dry summer periods even diurnal, cycles reflecting the change in glacier melt from summer to winter and night to day, respectively (Husebye, 1983). This is also noted within the lake, although the influence of the discharge variability becomes weaker with increasing distance from the inlet. At approximately one km from the

main inlet to southern Oldevatnet, the mean grain-size of sediment deposited during summer and autumn is practically identical, although the sedimentation rate is higher during summer (Husebye, 1983). The continuous sedimentation will therefore be more homogenous the further one moves away from the inlet, and consequently it is easier to distinguish periodic sedimentation at distal sites. Furthermore, the risk of disturbances related to slumping and erosion during rapid depositional events is reduced with increasing distance to the shore. A core retrieved at a distal and 'protected' site (OLP 105; see Figure 3) was therefore chosen for analysis of episodic sedimentation events in Oldevatnet.



Figure 4: Dirty, sediment-bearing snow floating around Oldevatnet following a snow-avalanche from the Beinnes colluvial fan (S2 in figure 3). Photo: Fjordingen.

The core analysis revealed more than sixty distinct 'event layers' featuring characteristics that indicated a sub-aerial origin, such as a notable content of terrestrial macrofossils. A few layers were interpreted to have resulted from high-magnitude flood events and possibly debris-flows (see paper I), however, the dominant episodic sedimentation process was reflected by layers consisting of poorly sorted, polymodal sediments containing abundant macrofossils and scattered dropstones. These layers were interpreted as the result of snow-avalanches. The erosive power of snow-avalanches in unconsolidated sediment and their role in landscape evolution has long been recognized (e.g. Rapp, 1960), as have their potential to deposit drop-stones in lakes after run-out on lake ice (e.g. Luckman, 1975). Even under ice-free conditions, a 'dirty' snow-avalanche is able to raft relatively coarse material into distal parts of a lake, as has been observed in Oldevatnet (Figure 4). This concept has previously been used to infer past snow-avalanche activity from the occurrences of coarse minerogenic grains in lake sediment cores (Seierstad et al., 2002; Nesje et al., 2007).

We identified forty-seven snow-avalanche layers over a time-span of 7300 years in Oldevatnet (Figure 5), which gives a mean recurrence interval of more than 150 years. It

may be questioned if such extreme events are representative for a general ‘snow-avalanche activity’. An analysis from the United States indicates that there is a power-law relationship between snow-avalanche size and frequency, similar to that of earthquakes (Birkeland and Landry, 2002), and if this relationship is applicable to western Norway an implication would be that the observed frequency of large avalanches is also indicative of snow-avalanche activity in general. The events recorded in Olden are not evenly spaced in time (Figure 5). For example, between 7200 and 5600 cal. yr BP, a period of 1600 years, no avalanches are recorded at all, whereas the last 400 years feature eleven snow-avalanche events. Increased avalanche activity is also recorded around 5500, 5000 and 1200 cal yr BP.

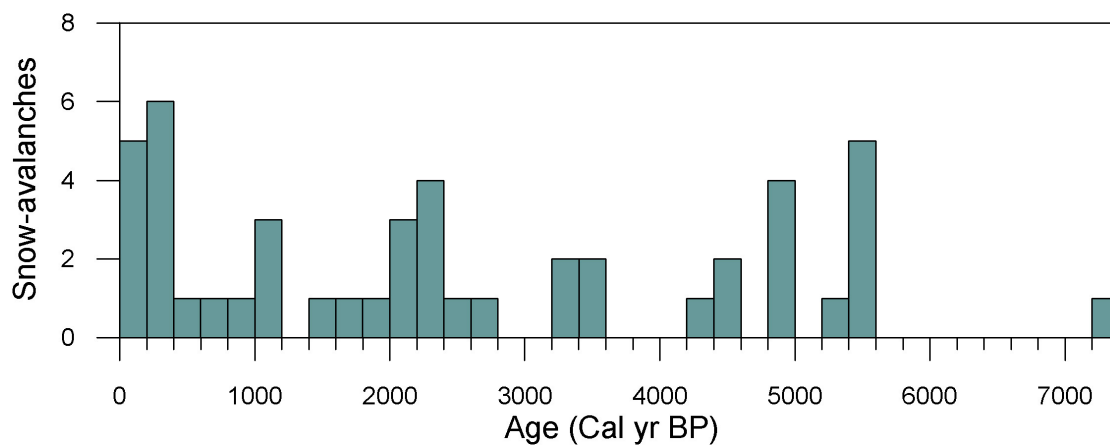


Figure 5: Snow-avalanche activity reconstructed from Oldevatnet (paper I) plotted as the number of avalanches per 200 years.

Among the different mass-wasting processes common to western Norway, snow-avalanches display the strongest statistical relationship with meteorological conditions (Kronholm and Stalsberg, 2009). Avalanches are triggered naturally when the gravitational load of the snow-pack overcomes a certain critical threshold of internal stability, usually as a result of additional loading through heavy snow-falls or wind-blown snow (Schweizer et al., 2002; Kronholm et al., 2006). This should make records of past snow-avalanche activity well suited for deriving information about past frequency of extreme weather events in the form of winter storms. There are, however, some caveats that complicate such interpretations. For example, it is difficult to explain why sometimes no avalanches are triggered even under ‘perfect’ meteorological conditions, mostly because it is difficult to predict the internal stability of the seasonal snow-pack and how it will react to additional loading (Schweizer et

al., 2002). Consequently, a geologic record of snow-avalanche activity reflects instances where complex interactions between weather, terrain and snow-pack conditions have crossed a certain threshold required to release an avalanche.

The links between long-term climate change and extreme events such as snow-avalanches remain elusive. A denser network of records will, however, allow performing more robust analyses of the temporal and spatial variability of extreme events through the Holocene, and how they might be connected to more dynamical aspects of Holocene climate such as atmospheric circulation patterns.

Paper II: Holocene glacier variability

Glacier erosion is presently among the most efficient denudation processes in the inner Nordfjord area (Owen et al., 2007) and thus considered very important for the sediment budget of the investigated fjord lakes. A number of palaeoclimatic studies have previously reconstructed Holocene climate change and glacier variability for the inner Nordfjord area (see Nesje et al., 1991; 2000a; 2001 and references therein). Glaciers in inner Nordfjord reached their maximum ‘Little Ice Age’ (LIA) extents around AD 1750, after which they have retreated significantly (Bickerton and Matthews, 1993). Outside the LIA maximum extent, the next set of marginal moraines are dated to approximately 10,000 cal yr BP (Nesje, 1984, 2009; Nesje et al., 1991), suggesting that the LIA advance was the second largest during the Holocene. As a glacier advances it tends to remove most of the unconsolidated sediment in its path, and consequently little terrestrial evidence from glacier variations between 10,000 cal yr BP and AD 1750 are left undisturbed in the Nordfjord region. Reconstructions of continuous Holocene glacier extent have therefore relied on proglacial lakes and their ability to reflect changes in the influx of glaciofluvial material (cf. Karlén, 1976; Nesje et al., 2000a, 2001). In order to tie changes in proglacial lake-records to glacier variability, sediment parameters have to be ‘calibrated’ against periods of known glacier extent and this is usually obtained from dateable moraine successions (e.g. Bakke et al., 2010). In areas where terrestrial evidence is lacking for longer periods, such as in Nordfjord, certain indirect evidence may nevertheless be indicative of past glacier size. This may include ‘on-off’ signals as recorded in the lake sediments, either caused by rerouting of glacial meltwater across local water divides (e.g. Dahl and Nesje, 1994; Bakke et al., 2010) or by the glacier crossing a bedrock boundary (e.g. Svendsen and Mangerud, 1997; Paasche et al., 2007). For studies aiming at reconstructing past glacier activity from proglacial lakes it is generally recommended to use a multi-site approach and focus on relatively simple glacial systems (Dahl et al., 2003). In paper II, however, we chose to investigate only a single proglacial lake situated distally in a large catchment housing over 50 individual glaciers (Figure 2 and 6). The motivation behind this approach was that if a glacier signal could be detected at this site, it would reflect the integrated response of all glaciers within the catchment. This would increase the probability of recognizing a regional climate signal (i.e. summer temperature and winter precipitation) by reducing the influence of local factors on glacier mass-balance such as topography and glacier aspect.

There is a complex relationship between discharge and sediment transport in glacial rivers. At any specific time the sediment yield is dependent on the previous history of transport and deposition, similar to a hysteresis effect (Østrem, 1975), which may be affected by changes in both sub-aerial and sub-glacial drainage routes. Over longer timescales, however, the internal dynamics of a glaciofluvial system should in theory smooth out, leaving the glacier activity in the catchment as the main controlling factor of downstream glaciofluvial sedimentation (Leonard, 1997). Sediment derived from other sources than direct glacier erosion will always constitute some part of the total transport in glacial rivers. Consequently, the further one moves away from the glaciers, the larger this non-glacial component is expected to become.

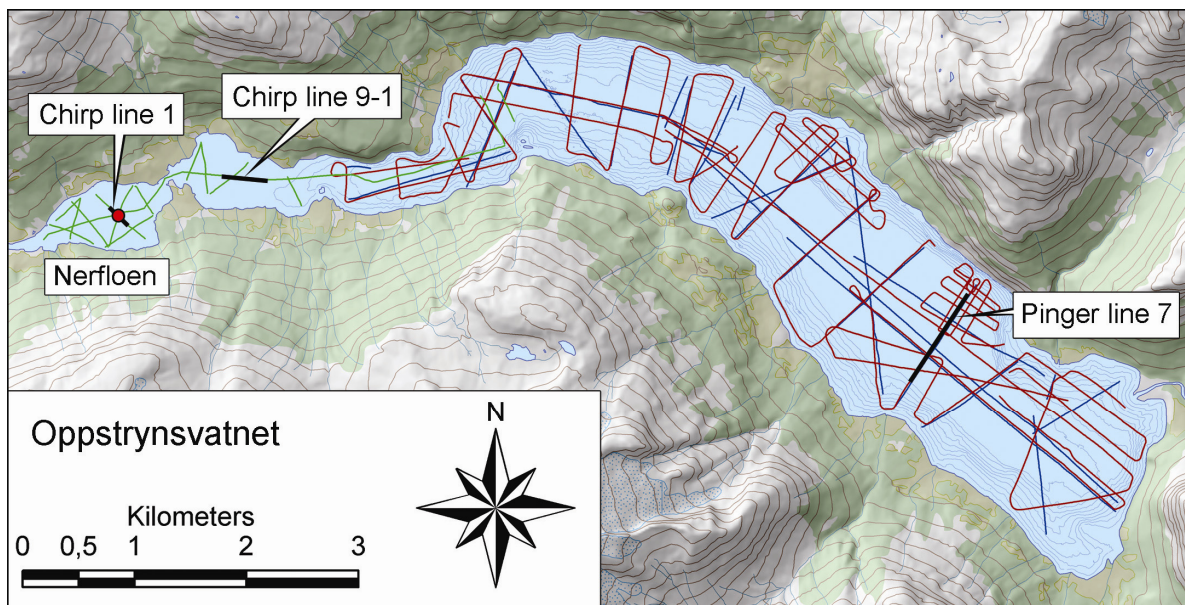


Figure 6: Oppstrynsvatnet and Nerfloen. Coloured lines indicate seismic profiles (Green = chirp; Blue = Pinger; Red = Airgun). Coring site of core STP 107 in Nerfloen is marked by a red dot. Black lines are seismic profiles shown in Figure 9. Contour lines are displayed at 100 m intervals on land and 20 m intervals in Oppstrynsvatnet.

Thus, the crucial task when reconstructing past glacier activity from a distal site is to un-mix the glacial from the non-glacial component of the bulk sediment. This challenge was addressed by selecting a study site where natural processes had already started the work of isolating the glacial component of the sediment. Nerfloen (1 km²) is connected to the much larger Oppstrynsvatnet basin (~30 km²), which receives glaciofluvial sediment from 52 separate glaciers within its 440 km² catchment (Figure 2). The 7 km² local catchment surrounding Nerfloen does not contain any glaciers, however, which provides crucial help in

interpreting the lake sediments. This means that in order to be deposited at the coring site, glacial sediment has to travel through Oppstrynsvatnet, which can be viewed as a 12 km long and 200 m deep, highly effective sediment trap. The search for glacially derived sediment could therefore be restricted to the finest grain-size fractions of the Nerfloen deposits.

A Principal Component Analysis (PCA) was applied to the multi-proxy dataset obtained from the Nerfloen sediment core (STP 107). It reveals a high co-variability between the fifteen investigated physical, sedimentological and geochemical parameters, and that 76% of the total variability of the dataset can be expressed by a single plot of the first principal component (1st PC) (Figure 7). Statistically speaking this suggests that a single process is responsible for most of the observed changes in the lake sediment parameters, and comparing temporal variations in the 1st PC to known glacier maxima and minima indicates that this process is in fact strongly connected to glacier variability. However, any climate-conditioned process, for example lake-water temperature or input of non-glacial minerogenic material from catchment runoff, may react in phase with glacier extent and cause the same reaction in a given sediment parameter (e.g. loss-on-ignition). This uncertainty is higher at distal sites than proximal sites, and therefore a measurable physical difference was needed in order to distinguish between glacial and non-glacial material with certainty. The parameter known as bulk magnetic susceptibility (χ_{Bulk}) was chosen for this purpose.

The ratio between χ_{Bulk} values measured at different temperatures (293K and 77K) reflects the balance between minerals featuring different magnetic properties, most importantly paramagnetic vs. ferri- and ferromagnetic minerals, within a sediment sample (Lanci and Lowrie, 1997). Because of the homogenous bedrock lithology of the Oppstrynsvatnet catchment, all sediment derived from local bedrock should initially display similar magnetic properties. Measurements performed on sediment samples from the catchment did, however, reveal large differences in the χ_{Bulk} values and the 77K/293K ratios in deposits of different genesis. Glacial deposits showed generally high χ_{Bulk} values and low 77K/293K ratios, whereas soil deposits sampled in the local Nerfloen catchment displayed the opposite. By comparing the χ_{Bulk} of relevant grain-size fractions from the catchment samples with the lake record it was possible to confirm the interpretation of the PCA as being closely tied to glacier activity.

Looking closer at the 77K/293K ratio of the lake sediment reveals that it behaves fairly stable close to the values 1 and 3, whereas the shifts in between are rapid. Values close to 3.5, also known as the ‘paramagnetic ratio’ (Lanci and Lowrie, 1997) implies that paramagnetic minerals dominate the sample, which suggest that non-glacial material dominates the sedimentary budget in the lake. Values close to 1 on the other hand reflect a dominance of ferri- or ferromagnetic minerals, reflecting ‘freshly’ eroded glacial material. The bi-stable behaviour of this parameter suggests that it is very sensitive around a certain threshold in the balance between glacial and non-glacial material, whereas towards the extreme ends of the scale it becomes less sensitive. This implies that it is not very well suited to reflect glacier changes within a sedimentary regime that is strongly dominated by either glacial or non-glacial sedimentation, although it is very well suited for pinpointing shifts between these states. As such it complements the continuous changes seen in the PCA by underlining periods where fundamental shifts in the sedimentary regime occur. This is particularly useful for identifying periods of significant glacier retreat during the Neoglacial (the last ~4200 cal yr BP). The strength of records based on lake sediments versus terrestrial records is the ability to reflect a continuous history of glacier change, including periods of glacier retreat. One of the most important contributions of the new glacier record presented in paper II is therefore a robust determination of the timing and extent of significant glacier retreats during the Neoglacial.

The maritime glaciers of western Norway are known to be sensitive to winter precipitation changes and variations in the North-Atlantic Oscillation (NAO) (Nesje et al., 2000b). Moving eastwards into the semi-maritime climate of the Jostedalsgreen area, summer temperature variations becomes more important (Nesje, 2005), and a comparison of the Nerfloen glacier record with temperature reconstructions from terrestrial and marine sites reveals many similarities (Figure 7). Glaciers are sensitive indicators of climate change, and the Nerfloen record adds significantly to the knowledge of Holocene glacier variability in inner Nordfjord by reflecting the integrated response of more than 50 single glaciers, including five major outlet glaciers from the Jostedalsgreen plateau glacier.

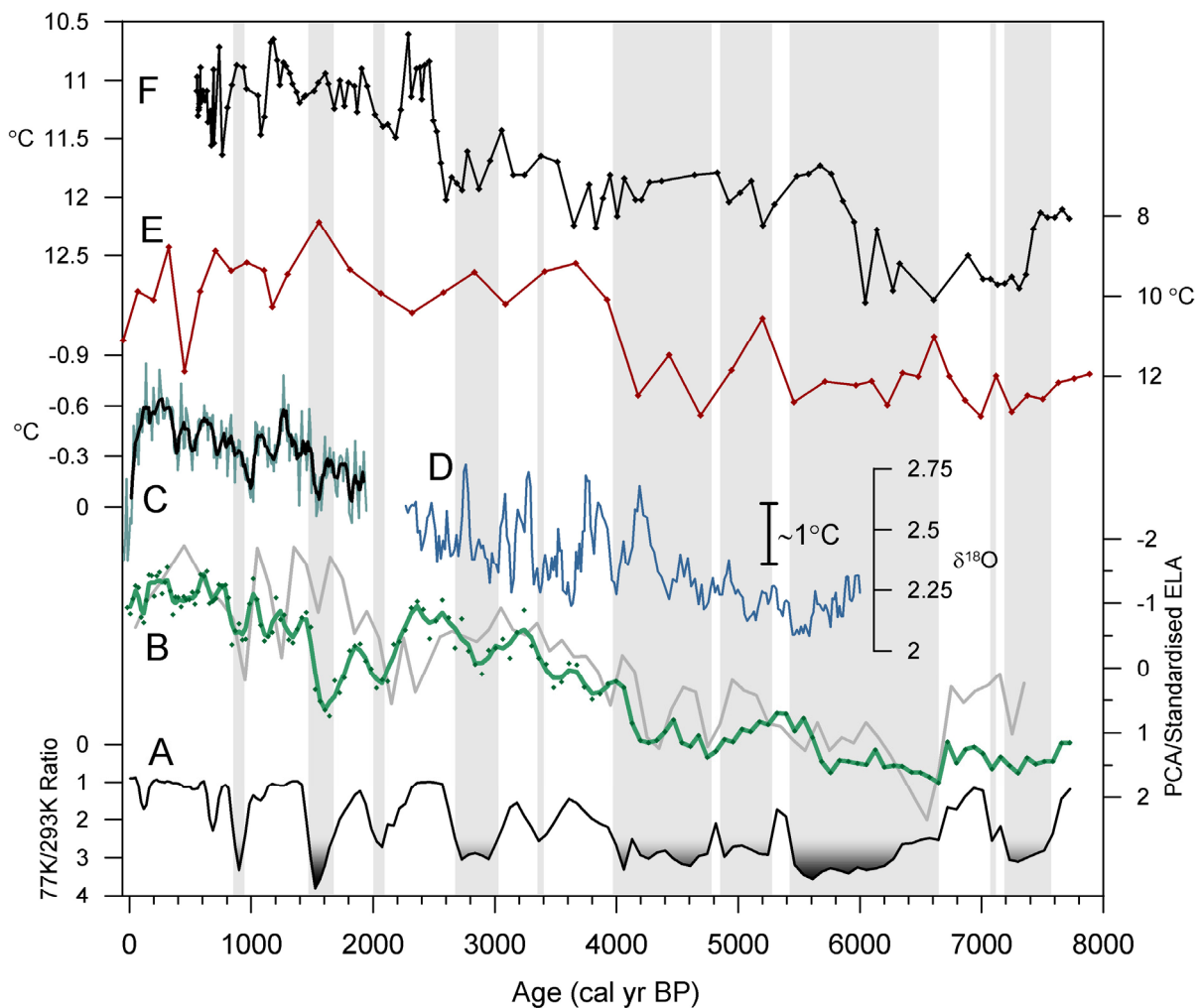


Figure 7: The glacier record from Nerfloen compared to different palaeoclimatic reconstructions. A: Bulk magnetic 77K/293K ratio from Nerfloen B) The PCA from Nerfloen (green line) compared to the previous ELA reconstruction from the Jostedalsgreen area (Nesje et al., 2001) (grey line). Note that the ELA record has been standardised allowing it to be plotted on same scale as the PCA C) Reconstruction of arctic temperature from terrestrial sites (Kaufman et al., 2009) with a 5-point running mean added (black line) D) Temperature reconstruction of bottom water in nearby Voldafjorden based on $\delta^{18}\text{O}$ values of the foraminifera *Cassidulina laevigata* (Kjennbakken et al., 2011) E) July temperature inferred from pollen in lake Trettetjønn (Bjune et al., 2005) F) SST reconstruction from the Vøring Plateau (Calvo et al., 2002). Note that all axes are inverted so that a rise in any of the temperature records signifies colder temperatures. Grey, shaded areas represent periods of significant glacier retreat in the Oppstrynsvatnet catchment relative to present glacier extent.

Paper III: The Storegga tsunami

Extensive bathymetric and seismic surveys along the Norwegian margin have revealed an enormous slide scar in the Storegga region, where approximately 3500 km³ of sediment has been displaced and deposited over an area of 95,000 km² (e.g. Jansen et al., 1987; Bugge et al., 1988), making it one of the largest known submarine slide events in the world. It was noted by Jansen et al. (1987) that such large submarine mass-movements are able to trigger giant waves, and that traces of a possible tsunami event “should be looked for” in Holocene deposits of adjacent coastal areas. Shortly after, distinct high-energy deposits were described from sites along the coast of Scotland (Dawson et al., 1988) and Norway (Svendsen and Mangerud 1990), and it was suggested that they were linked to a tsunami wave triggered by the main Storegga Slide. Later investigations were able to constrain the age of both the submarine slide (Haflidason et al., 2004) and the terrestrial tsunami deposits (Bondevik et al., 1997a) to around 7200 ¹⁴C years before present (~8100 cal yr BP), thereby demonstrate that the events were most likely linked. Following detailed descriptions and mapping of typical tsunami deposits from numerous sites in Norway by Bondevik et al. (1997a, b), traces of the Storegga tsunami has been discovered in an ever growing area around the North-Atlantic, which now spans from England in the south (Smith et al., 2004) to Greenland in the north (Wagner et al., 2007).

Numerical simulations of the Storegga tsunami have shown good agreement with mapped run-up heights along the outer coast of Norway, in Shetland and the Faroe Islands (Løvholt et al., 2005). An interesting aspect of the numerical models is that they predict a massive amplification of the tsunami wave towards the head of affected fjords (Løvholt et al., 2005), something that is in agreement with the large (>20 m) run-up reconstructed from fjord sites in Shetland (Bondevik et al., 2005). Along the Norwegian coast, however, evidence of tsunami impact inside the fjords has been scarce, although the models suggest a run-up of as much as 40 m at the head of Lysefjorden. An extensive search around the Hardangerfjord has not resulted in any clear evidence of impact by the Storegga tsunami (e.g. Romundset et al., 2010), and neither has any traces of the tsunami been found previously in Nordfjord (Lyså et al., 2010). This made it somewhat surprising when traces of the Storegga tsunami started to appear in Oppstrynsvatnet and Nerfloen, lakes situated 29 m a.s.l. at the head of Nordfjord more than 100 km from the outer coast (Figure 8) (paper III).

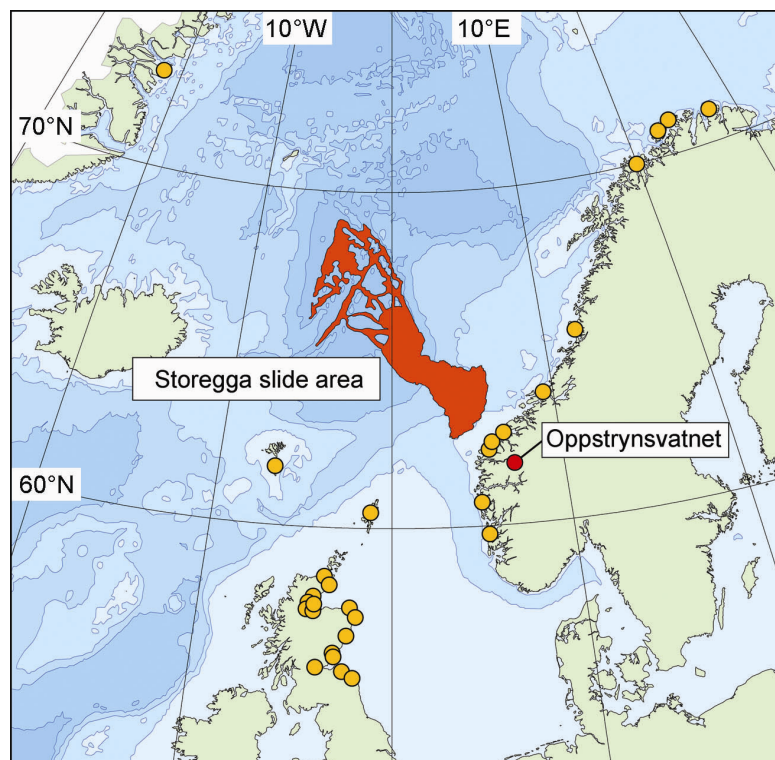


Figure 8: Map of the North-Atlantic showing the extent of the Storegga Slide and sites where traces of tsunami run-up have been reported (orange dots). Sites are compiled from Smith et al. (2004), Bondevik et al. (2005), Wagner et al. (2007) and Romundset (2010).

The first indication of a significant episodic sedimentation event in the early Holocene history of Oppstrynsvatnet was seen in the seismic profiles. An up to 2.5 m thick, transparent seismic unit covers large parts of the $\sim 30 \text{ km}^2$ lake floor at depths of 4-6 m below the sediment-water interface. It reflects a more chaotic internal structure than the continuous lake sedimentation, which features a distinct acoustic layering (Figure 9). Similar, extensive, transparent seismic facies observed in seismic profiles from lakes or fjords are usually interpreted as turbidites or mass-wasting events (e.g. Schnellmann et al., 2006; Waldmann et al., 2011). However, because of the relatively complex and laterally variable nature of the unit, the term ‘rapidly deposited layer’ (RDL) was used in paper III. In the shallower parts of the lake, close to the sill that separates Oppstrynsvatnet from Nerfloen, the seismic profiles reveal a strongly undulating topography in the deeper sediments, which is then suddenly cut at the base of the RDL around 2 m below the sediment surface (Figure 9). Locally, more than 2 m of the underlying sediments have been eroded at water-depths close to 20 m. In the outside Nerfloen lake basin this erosional hiatus forms a channel structure running longitudinally through the lake. The sediment core from Nerfloen was retrieved outside this channel in order to retrieve the base of the RDL. Although not very distinct in a visual sense,

the lithostratigraphic layer correlated to the RDL is revealed as being unique by a suite of sedimentological, physical and geochemical proxies (of which some are shown in Figure 9). The lowermost 15 cm features a smooth fining-upwards minerogenic succession, similar to a turbidite, revealing that it was deposited by a single episodic event. Above the turbidite a chaotic mix of coarse minerogenic particles and organic detritus make up a deposit that resembles a thick avalanche layer, although the presence of marine indicators within the mix suggest a more complex origin. This turbidite deposit and overlying terrestrial debris is correlated to the extensive RDL in the seismic profiles and interpreted as a result of the Storegga tsunami inundating the two investigated lake basins. The lowermost, minerogenic turbidite section in the core is interpreted to have formed as the energy from the tsunami wave gradually dissipated, whereas the upper, chaotic unit is interpreted as terrestrial detritus distributed across the lakes by the wave backwash. The strongest arguments for this interpretation are the highly erosive nature of the event and the minimum age of ~8000 cal yr BP obtained from numerous radiocarbon dates in the sediment core, which places it within the age estimate of the Storegga Slide (8100±250 cal yr BP).

It is not possible to directly infer the tsunami run-up in Stryn from the data presented in paper III. Data from the core suggest that the lakes were isolated from the sea around 9200 cal yr BP, and from previous sea-level studies it is known that the rate of emergence slowed considerably in the period between 10,000 and 7500 cal yr BP (Svendsen and Mangerud, 1987). The exact elevation of the lakes above sea-level at the time of the tsunami impact is therefore not known, although it seems improbable that it was more than 5 m. Some aspects of the tsunami deposit itself may, however, suggest a substantial run-up. If the percentage of terrestrial debris at the coring site is indicative for the tsunami deposit in general, this implicates that an enormous amount of terrestrial material was distributed across the lakes by the event, something that would further suggest that large vegetated areas were inundated by the tsunami wave. This is mere speculation at this point, however, and in order to properly reconstruct the tsunami run-up, suitable sedimentary basins in the Hjelledalen and Erdalen valleys should be investigated for traces of the tsunami.

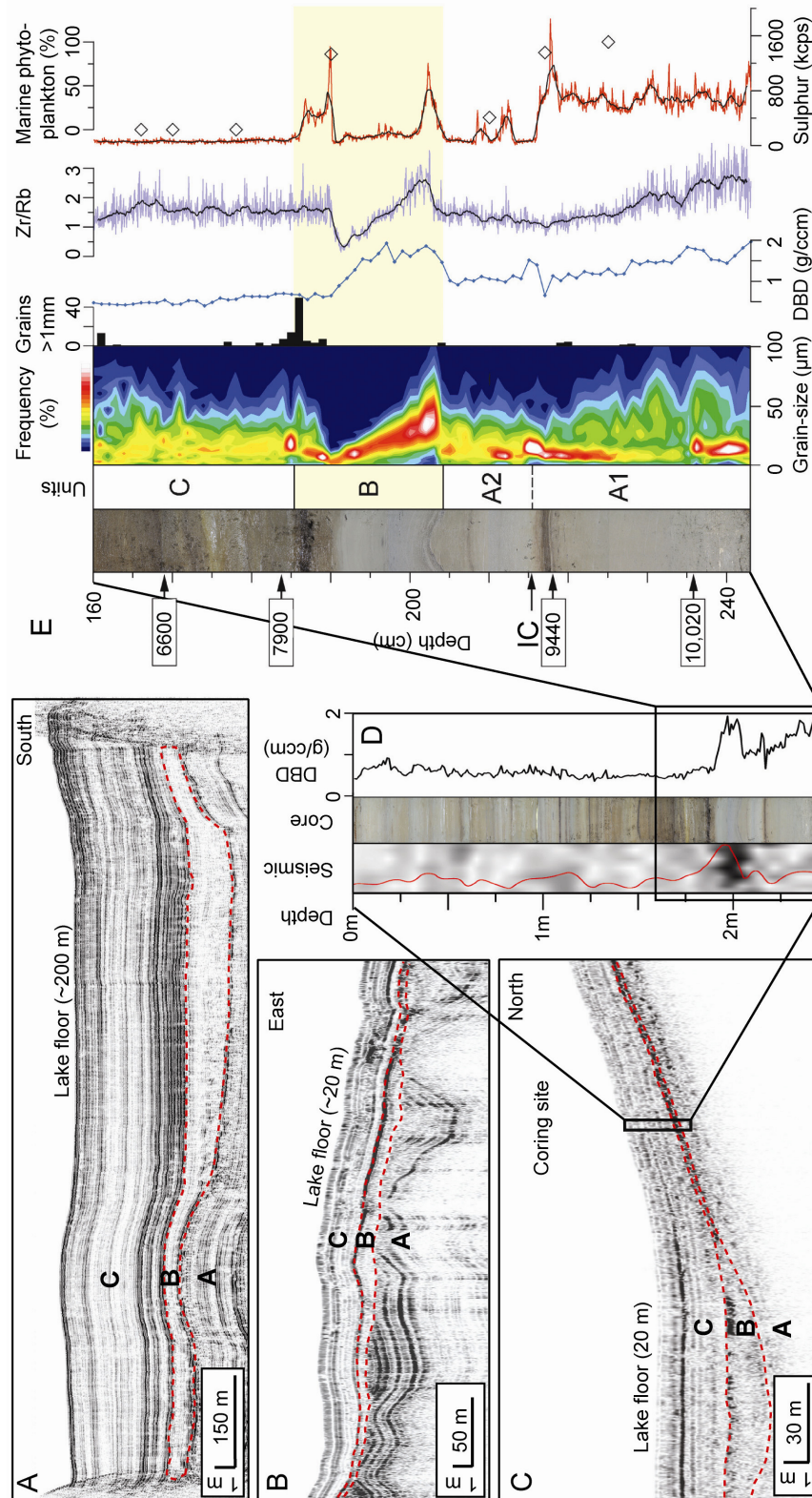


Figure 9: Selected seismic profiles from Oppstryvatnet (A and B) and Nerfloen (C), seismic to core correlation (D) and data from the STP 107 core (E). IC = Isolation Contact. Framed numbers are the weighted means of calibrated radiocarbon dates. Locations of seismic profiles are shown in Figure 6. The Storegga tsunami unit is named B in both the seismic profiles and in the core. Note the erosional hiatus in profile B).

Synthesis and perspectives

This thesis has described different approaches to how continuous and episodic sedimentary deposits can be distinguished in lake sediments. A careful consideration of site selection is needed for a successful lake study, and preliminary investigations such as bathymetric- and seismic profiling is invaluable in order to understand the sedimentary setting of a lake.

Results from paper I demonstrate that it is possible to reconstruct an undisturbed, continuous record of snow-avalanche activity from lacustrine sediments. The ability to record a high number of discrete snow-avalanche events is unique for the Oldevatnet record as compared to reconstructions from sub-aerial slope deposits (e.g. Blikra and Selvik, 1998) and previous lake investigations based on the influx of coarse grains (Seierstad et al., 2002; Nesje et al., 2007). A continued effort of reconstructing past flood- and mass-wasting activity is still required in order to increase our understanding of how such extreme events are connected to long-term climate change.

The new approach used for reconstructing past glacier variability presented in paper II may potentially be useful also in other areas. There are undoubtedly numerous sites with similar sedimentary settings around the world where the method may be successfully applied, and there is still much potential for further work in the Jostedalsgreen region. For example, similar studies could be performed in Floen (distal to Oldevatnet) and Hafslavatnet (south-east of Jostedalsgreen), as the area covered by the upstream catchments of these lakes includes a substantial part of the Jostedalsgreen glacier.

There is presently a concern that large rock-falls at sites within fjords in western Norway may create local, large-magnitude tsunamis. Such events will be restricted to a single fjord, however, whereas a tsunami generated in the North Sea has the potential to simultaneously enter fjords along the entire western Norwegian coast. Numerical models also suggest that the wave height of such tsunamis will be significantly amplified inside the fjords. Evidence of run-up from the Storegga tsunami in Oppstrynsvatnet and Nerfloen may be seen as the first verification of these numerical models, although the exact run-up height cannot be determined at present. This underlines that fjord areas in Norway and other parts of the world are not only vulnerable to local tsunamis triggered by rock-falls, but also tsunamis triggered in the open ocean by earthquakes or submarine slides.

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