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Relative sea level, deglaciation and tsunami history deduced from isolation basins

Coastal Finnmark and mid-Hardanger, Norway

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I do remember one thing.
It took hours and hours but...
by the time I was done with it,
I was so involved, I didn't know what to think.
I carried it around with me for days and days...
playing little games
like not looking at it for a whole day
and then... looking at it.
to see if I still liked it.
I did.
Adrian Belew - *Indiscipline* (1981)

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The results presented in this thesis depend most of all on high-quality field work. Coring operations on remote, subarctic islands in wintertime are not straightforward. My hard-working field assistants deserve sincere thanks for their patience, persistence and a good time in Finnmark; Ingvar Nørstegård Tveiten, Kristian Lindem, Elise Søyland and Hilary Dugan. Oddvar Romundset is also acknowledged for keeping the levelling rod steady. Working well inside the Younger Dryas moraine is much easier, still Jo Brendryen, Tore Humstad, Jan Henrik Koren and Aadne Sægrov should also be thanked for their efforts in Hardanger.

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Tromsø, May 2010

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Contents

List of papers

Paper I:

Romundset, A., Lohne, Ø.S., Mangerud, J. & Svendsen, J.I. 2010. The first Holocene relative sea-level curve from the middle part of Hardangerfjorden, western Norway. Boreas 39, 87-104.

Authorship statement

The research aims and strategy were planned by the main author in collaboration with John Inge Svendsen and Jan Mangerud. Øystein S. Lohne provided practical guidance prior to both field and laboratory work. The field work was planned and led by the main author, with assistance by all co-authors. All laboratory work was conducted by the main author, except for identification of diatoms that was done by Øystein S. Lohne. All co-authors contributed to the manuscript.

Paper II:

Romundset, A., Bondevik, S., Bennike, O. Holocene relative sea-level changes and deglaciation chronology in Finnmark, northern Norway. Manuscript to be submitted to Quaternary Science Reviews.

Authorship statement

The main author suggested, planned and conducted all the field and laboratory work. Stein Bondevik contributed with ideas that greatly improved the manuscript. Ole Bennike helped identifying some of the macrofossils and also commented on the manuscript.

Paper III:

Romundset, A., Bondevik, S. Propagation of the Storegga tsunami into ice-free lakes along the southern shores of the Barents Sea. Manuscript to be submitted as rapid communication to Journal of Quaternary Science.

Authorship statement

The main author suggested, planned and conducted all the field and laboratory work. Stein Bondevik contributed with valuable suggestions to the manuscript.

Scientific environment

Some of the data presented in Paper I were collected during the main authors MSc-studies at the Department of Earth Science, University of Bergen. This was later added to by more field- and laboratory work, and the paper was written at the Department of Geology, University of Tromsø. The work was part of the ICEHUS project led by Professor John Inge Svendsen and funded by the Research Council of Norway. Professor John Inge Svendsen, Professor emeritus Jan Mangerud and researcher Øystein S. Lohne, all at the University of Bergen, were active partners in the Hardanger project.

The work for Paper II and Paper III has been conducted during the main authors PhD fellowship at the Department of Geology, University of Tromsø. Work on the manuscripts was also conducted during a half-year stay at the University Centre in Svalbard. The research on tsunami deposits was initially part of the SPONCOM project at the University of Tromsø, from which funding was received for radiocarbon dating. An additional grant was given to the main author by the Roald Amundsen Centre for Arctic Research. Professor Stein Bondevik has been an active partner in the Finnmark projects.

Introduction

Research aims

The main purpose of this work has been to describe the relative sea-level history in two areas of Norway with high accuracy through time and space, by collecting and interpreting new field data from isolation basins. This method offers a unique opportunity to reconstruct shoreline displacement along the Norwegian coastline, but has previously been employed only in a few regions. Much of the presented work focuses on Finnmark, perhaps the region in Norway where the most comprehensive and detailed reconstructions have been made, but also a region virtually devoid of chronological data. A site well inside Hardangerfjorden has also been studied, where a rare cluster of isolation basins render it possible to produce the first precisely dated sea-level curve from a fjord site in Norway.

A secondary objective has been to use lake stratigraphy to map and date deglaciation and tsunami history. Lake basins often provide continuous sequences that hold complete archives of geological events, rather than scattered traces that can be found in surface deposits. Records of environmental changes, as well as tsunami erosion and deposition in near-shore basins, can therefore be found. Recent mapping of the seafloor has shown that several large slides have occurred at the Norwegian continental margin during the Holocene. Besides the much studied Storegga event, it is unknown whether tsunamis were triggered by these slides. Lakes that were close to sea level at tsunami time are likely to hold traces of such events.

Presentation of papers

The work included in this thesis is based on investigations of isolation basins in mid-Hardanger, South Norway (Paper I) and at the outer coast of Finnmark, North Norway (Papers II and III). The main focus has been on reconstructing the changes in relative sea level with high precision through the Holocene. The site Tørvikbygd in Hardanger was chosen because it is one of few places, well inside a fjord in western Norway, where isolation basins are found. Accurate data on relative sea-level change are important to palaeo ice-sheet modeling, since it puts constraints on the rate of glacio-isostatic adjustment after the last glacial, and in the case of Tørvikbygd, from an area where such data have previously been missing. The new reconstruction shows that the emergence rate was extremely rapid in the first millennium of the Holocene (> 5 cmyr^{-1}), before it slowed down and reached near standstill in the mid-Holocene. The shoreline has dropped about 16 m after the standstill until today. The results are further compared to data from a site outside the fjord mouth, and used to construct a shoreline diagram for Hardangerfjorden that deviates somewhat from previous undated morphology-based reconstructions.

Displacement of the shoreline has resulted in series of raised beach ridges in nearly every bay of Finnmark, and has been studied by Quaternary geologists for more than a century. Still, almost no chronological data have been obtained, due both to scarcity of datable material onshore and to the fact that no systematic isolation basin study has been undertaken. In Paper II, radiocarbon-dated isolation basin sequences used for reconstructing sea-level curves from three areas at the outer coast are presented. These curves document the timing and magnitude of the mid-Holocene Tapes sea-level fluctuation at the localities. At the easternmost locality, evidence is also found that the strong early Holocene uplift, that took place along most of the Norwegian coastline, was here delayed for about 1000 years. The data show that the gradient of Holocene raised shorelines in Finnmark is significantly lower than in comparable coastal regions of western Norway. This is attributed to the fact that coastal Finnmark lies in the periphery of the former Barents Sea Ice Sheet, and that rebound of the seafloor affected the coast in addition to the rebound from the Fennoscandian Ice Sheet. The (earlier) demise of the Barents Sea Ice Sheet and the following rebound is also the reason for anomalously high marine limits along the outer coast of Finnmark.

A number of mollusk shells and macro-algae samples from basal lake sediments both in Hardanger and Finnmark have been dated and used to reconstruct the timing of regional ice-sheet retreat. These show that the fjord glacier in Hardangerfjorden retreated inland of the study site around 11,300 yr BP, whereas the outermost coast of Finnmark likely became ice free following the huge temperature rise at the onset of Bølling, ca. 14,600 yr BP.

Traces of strong erosion and deposition were also found in five lakes in Finnmark (Paper III). The characteristics of the erosion and deposits leave little doubt that a tsunami inundated the lakes, and ages obtained on material picked from within or just above the deposits correlate to the ca. 8100-8200 cal yr old Storegga tsunami. It is thus shown for the first time that the Storegga tsunami propagated into the Barents Sea, and reached at least 1300 km distance from the slide. Based on the pattern of erosion, the inclusion of both rip-up peat clasts and sand-coated gyttja clasts and the sorting of sediments deposited by the tsunami, it is concluded that this took place when the lakes were not ice-covered and the ground not frozen, thus the Storegga slide and tsunami event occurred in the summer season.

Norsk samandrag (Summary in Norwegian)

Denne avhandlinga tek for seg endringane i relativt havnivå – strandforskyvinga – dei siste vel 11.500 åra på kysten av Finnmark og i midtre Hardanger. Ei stor mengd kjerneprøver frå avsettingane i innsjøar som ein gong låg under havnivået, er henta inn og analysert. Grenser mellom sediment som vart avsett i salt- eller ferskvatn er bestemt ved å analysere både kiselalgar og restar etter daude dyr og planter, og tidfest ved hjelp av radiokarbondatering. I lag med presist oppmålte høgder på innsjøtersklane, gjer desse data det mogleg å rekonstruere havnivåendringane i høg detalj. Her blir det presentert havnivåkurver som syner utviklinga i fire område; Tørvikbygd i Hardanger, Sørøya og Rolvsøya i vest-Finnmark og Nordkinnhalvøya i aust-Finnmark. Desse dokumenterer samspelet mellom landheving og havnivåstiging – stort sett har landhevinga vore sterkast, men i tida mellom ca. 9-7000 år sidan var det motsette tilfelle på finnmarkskysten – da vart fleire innsjøar atter oversvømt etter å ha lege fleire tusen år over havnivået. På Rolvsøya steig havnivået opp over ein innsjø men nådde ikkje den neste som ligg rett attmed, berre omlag 60 cm høgare. Her stabiliserte det seg i meir enn tre tusen år, fram til for ca. 5000 år sidan. Etter det har havnivået falle fleire meter fram til i dag. Ei liknande utvikling er òg funne på Sørøya og Nordkinnhalvøya, men i Tørvikbygd er historia ei anna. Her vart landet mykje hardare nedpressa mot slutten av siste istid, og landhevinga har vore tilsvarande sterk, særleg det fyrste tusenåret etter at isen forsvann – da datt strandlina gjennomsnittleg med meir enn 5 cm i året.

Breen som dekte Barentshavet under siste istid, smelta vekk tidlegare enn isen over Finnmark. Dette førte til sterk heving av havbotnen som også virka inn på tidleg isfrie område av ytterkysten og medførte at spranget mellom marin grense og yngre strandliner er langt større her enn langs andre delar av norskekysten. I tillegg er bidraget til hevinga frå Barentshavet, truleg i lag med ein slakare profil på innlandsisen, årsaka til at dei heva strandlinene i Finnmark hallar mindre enn dei gjer t.d. på Vestlandet.

Det er funne klåre spor etter ein tsunami i fem av innsjøane på Finnmarkskysten. Dateringar syner at dette må ha vore Storeggatsunamien, som vart utløyst av eit enormt undersjøisk skred utafor Mørekysten for om lag 8100-8200 år sidan. Bølgja slo opp i alle fall 3-4 meter i høgda, og mange hundre meter innover land. Erosjonen var sterkast nært sjøen der tsunamien grov seg ned i meir enn 3000 år eldre avleiringar. Over erosjonskontakten ligg nedst eitt sandlag, fylgd av mellom anna opprivne torvbitar og gytjeklumpar som tydeleg har rulla i sanda. Den valdsamme erosjonen og dei sorterte avsettingane tilseier at tsunamien må ha råka innsjøar som ikkje var islagte, og på denne tida var klimaet vesentleg kaldare enn i dag. Dette gjer det truleg at både Storeggaskredet og tsunamien hende ein gong mellom april og oktober.

Background and perspectives

Sea-level changes

The eustatic component of sea-level records provides a measure of the mass transfer occurring during glacial-interglacial cycles. Frozen water stored on land was responsible for a 125±5 m lowering of global sea level during the peak of the last glaciation as compared to the present (Fleming et al. 1998). Furthermore, the mass held by the two present ice sheets equals ~70 m if added to the ocean (Alley et al. 2005). Knowledge of the behaviour and change rates of former ice sheets, and of the related palaeo-record of sea-level changes is therefore crucial; not merely to our understanding of earth history, but also to potential future changes (e.g. Long 2009; Siddall et al. 2010).

During the last glacial, a vast ice sheet covered north-western Eurasia, extending from the British Isles to north of Svalbard and east into Russia (Ehlers and Gibbard 2004). The sedimentological, stratigraphical and geomorphological imprints left by the ice have been used to reconstruct the configuration of the different parts of the ice-sheet through time. Glaciological and climate information is also used in numerical forcing models to reproduce realistic ice sheet development (e.g. Elverhøi et al. 1993; Lambeck et al. 1998; Siegert and Dowdeswell 2004). An important parameter in palaeo-ice sheet modelling is the inverted isostatic rebound data extracted from sea-level records found onshore (Lambeck and Chappell 2001). The validity of a model thereby depends largely on the accuracy of these data; the reliability of sea-level indicators and their chronological control.

The study of sea-level history and shoreline displacement is a classic discipline in Scandinavian geosciences, and along parts of the Norwegian coastline the development has been relatively well constrained, especially through the application of isolation basin investigations (e.g. Anundsen 1985; Kjemperud 1986; Svendsen and Mangerud 1987; Corner and Haugane 1993; Lohne et al. 2004, 2007). However, reconstructions for some areas rely fully on undated morphostratigraphy and correlations to other regions. This is especially the case for large parts of northern Norway, and also for inner fjord areas, since most studies have been conducted at the outer coast. Radiocarbon ages of shells found in raised marine deposits are notoriously ambiguous due to uncertainties in levelling, relation of the deposit to mean tide sea level, ecological range and feeding mechanism of shell species, and potentially inaccurate marine reservoir ages. The lack of precise data in some regions is a major disadvantage to present models that make use of inverted isostatic rebound data (Lambeck et al. 1998, 2010).

Tsunamis in the North Atlantic

The public interest in tsunamis was greatly raised after the 2004 Indian Ocean event, which also sparked new initiatives to look into the geological history for evidence of the recurrence frequency of Indian Ocean tsunamis (e.g. Jankaew et al. 2008; Monecke et al. 2008). However, since the first discoveries of deposits from the Storegga tsunami were made, more or less simultaneously in Norway and Scotland (Svendsen 1985; Dawson et al. 1988), much research on tsunami deposits has been undertaken in the less tectonically active North Atlantic region. The Storegga slide triggered the most prominent tsunami event 8100-8200 years ago (Dawson et al. 1988; Bondevik et al. 1997a), which spread across the North Atlantic, hit Greenland (Wagner et al. 2006) and, as it is shown in this thesis, also propagated into the Barents Sea (Paper III: Romundset and Bondevik). Evidence of other, presumably less widespread, tsunamis have been unearthed on Shetland (Bondevik et al. 2005a), and other submarine slides that could have triggered tsunamis in the North Atlantic have also been mapped (van Weering et al. 1998; Laberg and Vorren 2000; Laberg et al. 2000; Kuijpers et al. 2001).

Tsunamis may leave signatures in various geological records; they are most commonly studied along shorelines, but can also be found in deep sea records (Dawson and Stewart 2007). Convincing evidence of tsunami traces are however hard to prove; minor abnormities seen in various records are hardly sufficient to draw confident conclusions (e.g. Lyså et al. 2004; Cohen et al. 2006; Jordan et al. 2009; Mills et al. 2009). Coastal lake basins are presumably the best tsunami traps; their continuous background sedimentation causes erosion and deposition by a tsunami to clearly stand out in the lake record (Bondevik et al. 1997b), but in most areas no systematic search for tsunami deposits in coastal lakes has been undertaken.

Deglaciation chronology

Relative sea-level changes and glaciation history are closely related; not only through ice volumes and eustatic sea level, but also through the relaxation of the crust that occurs during and after deglaciation. In many deglaciated regions, the glacio-isostatic rebound pattern is visualised by staircases of raised shorelines that, along with end moraines, are perhaps the most direct evidence of former glaciations. Indeed, observations of raised, tilted shorelines in

Finnmark (Bravais 1842) were important to the general acceptance of the theory of glacial isostasy (De Geer 1888/1890), and it was the finding and dating of driftwood at 100 m a.s.l. in central Svalbard (Salvigsen 1981) that finally convinced the majority of geologists that Svalbard and the Barents Sea had been fully glaciated during the last ice age.

The chronology of ice-sheet recession in Hardangerfjorden and in coastal Finnmark is discussed in light of new findings in Paper I and II, respectively. A number of chronologically constrained glaciation curves for transects of Norway have been published since the advent of the radiocarbon dating method, and today most reconstructions rely heavily on radiocarbon measurements – often of marine material. However, the many pitfalls and sources of error associated with radiocarbon dating make accurate chronologies hard to achieve, especially for the Lateglacial when most of the glacial recession took place (Birks and Seppä 2010).

Many ages from terrestrial archives stem from bulk samples where hard water and inorganic carbon may cause large errors. Paper I (Romundset et al. 2010) partly concerns an exhaustive debate that has been going on for more than a decade, dealing with the ice-sheet configuration during deglaciation in this part of western Norway (Helle et al. 1997; Mangerud 2000; Bakke et al. 2005; Lohne 2005; Helle 2008). The reliability of radiocarbon-dated bulk gyttja and the lack of precision around the 10 ^{14}C kyr plateau of the calibration curve have certainly been key issues in this debate. The development of Accelerator Mass Spectrometry (AMS) ^{14}C-dating in the mid 1980's increased the sensitivity of the radiocarbon dating method greatly and made it simpler to obtain accurate ages of small samples of organic material. It thus became possible to avoid potentially erroneous ages of bulk samples (Björck et al. 1996), but it remains a challenge to find sufficient amounts of identifiable terrestrial plant material.

In Paper II we discuss the chronology of ice-margin retreat in Finnmark. Current reconstructions are based on correlation of radiocarbon measurements over large regions. These measurements are from marine material, found in raised marine deposits or core samples from the seafloor, and somehow associated with reconstructed ice-margin positions (Vorren and Plassen 2002). The ages that are used for correlations are most often cited as the mean value of a collection of radiocarbon measurements, rounded off to nearest hundred or thousand ^{14}C-year. There are a number of uncertainties and sources of error involved in such an exercise. Firstly, attempts to distinguish events in time should not be made without considering the full 2σ age distribution of the radiocarbon measurement after calibration to sidereal years. This will, in many cases, result in long and overlapping age intervals, but these represent the real resolution of the data.

Moreover, the accuracy of radiocarbon measurements of marine material from the Lateglacial is notoriously hampered by the unknown, probably large, variability of the marine reservoir age (Björck et al. 2003; Bondevik et al. 2006). Also, many of the shells that have been frequently dated, stem from mollusks that live in the sub-surface and could be contaminated by "old" ambient water and absorption of old carbon from the sediments (Thomsen and Vorren 1986; Vorren and Plassen 2002; Mangerud et al. 2006).

The radiocarbon dating method thus has limited use for detailed reconstructions with the time-resolution needed for distinguishing events such as small ice-margin oscillations; particularly so if ages are based on marine material from the Lateglacial. Correlations of age estimates between regions should not be made without also carefully considering the associated uncertainties.

The isolation basin method

The main method used in this work is isolation basin analysis. The principles for the method are therefore outlined below. Some of my own experiences with the method are also noted.

What is an isolation basin?

Most of Fennoscandia is characterised by a glacial landscape where numerous erosional depressions were left by receding glaciers following the last glaciation. Bedrock basins situated below the marine limit may hold a record of shifts between marine and lacustrine sedimentation. Such basins therefore offer unique possibilities to describe postglacial sea-level fluctuations in great detail, as already suggested by Sundelin (1917). The advent of the radiocarbon dating method strengthened the value of basin investigations, and the technique was much developed by Hafsten (1960) who named this the “isolation basin method”. Since then, and most frequently in the last two decades, numerous studies have made use of isolation basins; along the Norwegian coastline (e.g. Kjemperud 1986; Svendsen and Mangerud 1987; Corner and Haugane 1993; Corner et al. 1999; Lohne et al. 2007), elsewhere in Scandinavia (e.g. Seppä 2000; Eronen et al. 2001; Lindén et al. 2006; Yu et al. 2007), in northern parts of the British Isles (e.g. Shennan et al. 2000), Greenland (e.g. Long et al. 1999, 2008; Bennike et al. 2002; Sparrenbom et al. 2006a), Iceland (Lloyd et al. 2009), Canada (Miousse et al. 2003; Hutchinson et al. 2004; Smith et al. 2005), Russia (Corner et al. 2001) and Antarctica (Zwartz et al. 1998; Verleyen et al. 2004; Bentley et al. 2005).

The basin threshold

The accuracy of an isolation basin study depends on the ability to correctly determine the threshold elevation, and to pinpoint and date the isolation boundary. Basins with well-defined bedrock thresholds are preferred, since significant post-isolation incision then can be ruled out. However, such basins are not always available. Moraine-dammed lakes provide a next-best alternative; here it is reasonable to assume that most erosion took place during disconnection from the sea, and not after the tide current had stopped streaming across the threshold. Lakes and bogs dammed by beach ridges, as well as depressions in marshy areas, both of which are numerous in northern Norway, should be avoided due to uncertain threshold elevations and incomplete records. The lake elevations may be acquired from maps, or at best levelled in field. The present mean-tide level has often been used as basis for levelling near-shore features. This can be found either by daily observing the high tide during field work, and then correcting to mean tide level using local tidal amplitudes (e.g. Long et al. 1999, 2008), or by assuming rough correspondence between the mean tide level and the upper growth limit of barnacles (*Balanus* sp.) or bladderwrack (*Fucus vesiculosus* sp.) (e.g. Sollid et al. 1973; Donner et al. 1977; Krzywinski and Stabell 1984). However, the altitude of official benchmarks are in Norway given with a precision of about ± 0.05 m (NHS 2010); if such are found near the study site they will provide a more accurate basis for levelling.

The isolation process

At some point during disconnection from the sea, the lake salinity becomes sufficiently reduced to cause depletion of dissolved oxygen. The anoxic conditions in turn reduce bioturbation at the lake bottom and allow for sedimentation of laminated sediments. Isolation boundaries are therefore often readily visible in the lake sequence. The same, but inverted, development takes place when RSL rise inundates a lake basin, then depositing an ingression boundary.

A shift in various properties of the sediments is often recorded at the upper limit of the laminated segment of the stratigraphy (see discussion below), but this correspondence is not always straightforward. Depending on the rate of RSL change, the laminated segment can make out cm to m long segments of the stratigraphy. Moreover, the basin volume, morphology and its through-put determines how rapid the decline in salinity will occur. Indeed, deep, sheltered lakes that have been isostatically raised tens of metres above present sea level and still hold trapped salt water at the bottom, have been found several places in Norway (Strøm 1957, 1961; Holtan 1965; Barland 1991). In such basins, deposition of laminated sediments at the lake floor may continue as long as anoxic conditions are conserved. However, this is not relevant to most isolation-basin studies, since in most cases small and shallow basins are used.

Determining marine-lacustrine boundaries

Several different methods have been used to demonstrate the exact level of the marine-lacustrine isolation/ingression boundary. Diatoms are photosynthetic and track salinity changes in the upper surface water (the photic zone); they are therefore not affected by potentially stagnated bottom water and most often used. The interpretations in Paper I (Romundset et al. 2010) are based on a simplified check of the diatom assemblage to identify the dominant species and associated environments. The upper boundary of laminae often corresponds to the shift in the diatom flora that is recorded in the sediments, and marks the time when water in the photic zone had been exchanged (Kjemperud 1986). Other, less widely used, proxies include pollen and phytoplancton analysis (e.g. Kaland 1984a; Svendsen 1985), and more readily attainable core data like loss on ignition (LOI), grey scale analysis, lithostratigraphy, sedimentary changes, magnetic susceptibility (MS) and X-ray fluorescence spectrometry (XRF) scanning. In central Sweden, boundaries deposited during rapid regression have been detected merely by the visual sediment change and MS and LOI values (Berglund 2004; Lindén et al. 2006), whereas the adequacy of using solely XRF data was discussed by Sparrenbom (2006).

The basin record of plant and animal macrofossils constitutes yet another proxy for palaeosalinity, and was used in the analysis of isolation boundaries for Paper II: Romundset et al. It has to the authors knowledge only been used previously by O. Bennike and C. J. Sparrenbom in Greenland (Björck et al. 1994a, 1994b; Bennike 1995; Bennike et al. 2002; Sparrenbom et al. 2006a, 2006b; Wagner et al. 2010), once in Québec, Canada (Miousse et al. 2003) and once along with diatoms in central Norway (Solem et al. 1997; Solem and Solem 1997). The latter authors identified Chironomidae and Trichoptera to genus level, and maintain that the macrofossils track the environmental changes more precisely than the diatoms do. Also, the fossil midge stratigraphy was found to closely track the salinity change after lake isolation in eastern Canada (Rosenberg et al. 2005; Heinrichs and Walker 2006). Many organisms that are common in the basin stratigraphies are unique to marine or limnic environments; the biostratigraphy therefore indubitably documents both basin isolation and reconnection to the sea.

What tide level is reflected by the boundary?

The exact relation of sea tide level to the lake record has not yet been satisfactorily demonstrated. The most common assumption is that the surface water does not become fully fresh as long as the lake basin receives salt water twice a month, during highest astronomical spring tides (HAT) (Kjemperud 1986). Consequently, the age of the isolation boundary in a core, and in most cases the upper limit of laminated sediments, corresponds to the time when HAT reached to the basin threshold. However, ambiguities in diatom records have resulted in a contradicting view; that laminated sediments become deposited after isolation from the sea (Corner and Haugane 1993; Corner et al. 1999, 2001). Following this, the lower boundary of the laminated sequence is the actual sedimentological signature of when HAT stood at the basin threshold, and incidents of marine diatoms in the laminated sequence are explained by inundation during storm surges. The difference in age of the upper and lower boundaries equals the time of deposition of the laminated sequence. These different interpretations are therefore only decisive where the laminated sequence is deposited over a time span divisible by the radiocarbon dating method.

Indeed, very low atmospheric pressure combined with strong onshore wind may cause local sea level to swell well above HAT during storm surges. At most standard ports along the outer Norwegian coastline, storm-surge sea levels around 50 cm above HAT have been recorded (NHS 2010). In the harbor of Oslo the effect becomes amplified by the long and narrow Oslofjord and local sea level was in the year 1914 recorded 159 cm above HAT level (NHS 2010). Storm surges will obviously supply marine water to a recently isolated lake and must be accounted for when deciphering marine/lacustrine transitions in sediment cores. However, it is reasonable to assume that the most considerable change takes place when the bimonthly HAT no longer reaches above the threshold, since flooding above HAT will happen much more rarely than twice a month. It will then cause only minor incidents of marine water, with scattered occurrence of a few marine diatoms and organisms above the isolation boundary as a result. This interpretation is followed in Papers I and II.

Dating the boundary

Correctly determined marine-lacustrine boundaries still need to be accurately dated. Terrestrial plant macrofossils are preferential to bulk gyttja samples, since potential contamination and reservoir effects due to inclusion of marine (Corner et al. 1999, 2001) or limnic (e.g. Kaland et al. 1984b) material then are avoided. However, finding sufficient amounts of material from a thin cross-cut slice of the core is a time-consuming and challenging task, and might not be feasible (Eronen et al. 2001; Lindén et al. 2006).

Additional results – macrofossils vs. diatoms

Plant and animal macrofossils were used to determine the marine-lacustrine boundaries in the lake cores from Finnmark. Based on the results, it is concluded in Paper II that the biostratigraphy firmly documents isolation and ingression events. In order to substantiate this conclusion, the biostratigraphy was compared to the diatom record of two sequences; from the post-Tapes isolation of Lake 5 and the segment of increased marine influence of Lake 6 (Paper II: Romundset et al.). The results are compiled in modified versions of the macrofossil diagrams from Paper II, combined with the interpretation from the diatom check (Figs. 1 and 2). Details on diatom species are given in Tables 1 & 2.

Lake 5 – Isolation boundary (Fig. 1, Table 1)

The interval shown in Fig. 2 covers the inferred isolation boundary of this lake, dated at 680 cm depth to ca. 5000 yr BP (Paper II: Romundset et al.). It also includes samples from the upper 40 cm of a blackish and densely laminated deposit found between 735-680 cm. The thickness of laminated sediments indicates that long-lasting anoxic conditions prevailed at the lake bottom, due to the slow rate of land emergence at the time when the lake became isolated. Still, both diatoms and macrofossils document fully marine surface water during deposition of the laminated sediments at 720 cm. Samples at 700 and 695 cm show a mixed brackish/marine diatom assemblage, where e.g. tests from the foraminifer *Egerelloides scabrum* and exoskeletons from Hydroidea still occur in large numbers. Limnic macrofossils are only represented by few Chironomidae larval head capsules at these levels. At 690, 685 and 682 cm, the diatom assemblage is also mixed, with an increasing input of lacustrine species. *E. scabrum* is still present at 690 cm, but above that level, only few remains from a couple of marine organisms are found. The exception to the lack of macrofossils around the upper limit of laminae is Chironomidae, which rapidly increases in numbers to hundreds of head capsules per cm^3 in the uppermost laminated sediments. Homogenous, non-laminated gyttja is found above 680 cm. A few brackish diatoms at 678 cm indicate still some input of marine water, but at 675 cm there are only lacustrine species. Likewise, macrofossils from only a few limnic (and no marine) species are found at 680 cm, but at 675 cm the sediment is rich in several limnic species, e.g. many *Nitella* oogonia and *Cristatella mucedo* statoblasts that clearly document fresh water in the photic zone.

Lake 6 – Marine influence on the lake environment (Fig. 2, Table 2)

The presented interval covers ca. 1 m of sediments, thought to have been deposited over a period of ca. 3000 years in a lake situated just above high-tide sea level, with varying influence by sea spray and/or storm surges (Paper II: Romundset et al.). The sediment is vaguely banded throughout, with slightly fluctuating loss-on-ignition between 15-30 %; typical values for lake gyttja. Both macrofossils and diatoms have a mixed assemblage of limnic and marine species from the lowermost sample at 415 cm up to 330 cm, with a possible slight decrease in marine input above ca. 350 cm. A sample at 310 cm depth holds only limnic species, e.g. numerous *Plumatella repens*, which indicate fully fresh surface water and that the (minor) marine influence had ceased.

Conclusion

Dr. Øystein S. Lohne at the University of Bergen checked the diatoms and made the environmental interpretations thereupon, following the procedure outlined in Paper I (Romundset et al. 2010). He made the interpretations independently, without knowing the results from the macrofossil analysis. Still, the environmental interpretations and decisions both for placing the isolation boundary (Lake 5) and not being able to detect a boundary (Lake 6), were the same. The sudden rise in the number of limnic organisms at or just above the isolation boundary is the most pronounced feature of the macrofossil record in Lake 5, and the similar development has also been found in most of the other basins investigated in Finnmark (Paper II: Romundset et al.). The rise corresponds directly to the upper limit of the laminated sediments, at which level also limnic diatom species become dominant. The results leave little doubt that marine water completely dominates the surface water of the lake during deposition of the laminated sediments.

Ideas for future research

- The potential of isolation basins studies is highlighted through this work. There is an increasing need for high-precision palaeo-sea level data, both to use as important constraints for ice-sheet modelling, and as a reference for possible changes in the future. No other method provides as precise data as an isolation basin in this context. Norway has a coastline where raised bedrock basins in many areas are extremely common and we therefore have an advantage over many other regions in the world.

- In Finnmark, more sea-level data from further east and inland would much improve our understanding of the deglaciation and rebound history in this area that was affected by two different ice sheets. Based on map and aerial photograph surveys, the land surrounding Tanafjorden and Varangerfjorden stands out as an area with abundant raised bedrock lakes spread geographically and found at most elevations between the present shoreline and the marine limit. The chronology of shoreline displacement in this area is also of particular interest to archaeologists due to the local abundance of findings related to early immigration of humans to northern Fennoscandia. The terrain and snow and ice conditions in this region are good for efficient winter field work. Extensive lake coring in this region is therefore likely to yield comprehensive and highly precise information on the sea-level history.

- A challenge when reconstructing the Lateglacial part of sea-level histories based on isolation basins can be to find sufficient amounts of identifiable terrestrial plant material for dating the marine-lacustrine boundaries. Other dating methods such as OSL and exposure dating could potentially be used for the uplifted beach deposits found above the Main shoreline, results thereof would add to and improve the reconstructions presented in this thesis.

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Table 1. Results from the diatom check, Lake 5 Storvatnet

Depth (cm)	**Indicator diatoms**	**Basin environment**
660	*Cyclotella sp.* (OI?), *Fragilaria pinnata* (OI), *Fragilaria virescens* (H), *Cymbella minuta* (OI), *Tabellaria fenestrata* (H), *Tabellaria flocculosa* (H), *Pinnularia interrupta* (OI), *Fragilaria construens* (OI), *Aulacoseira sp.* (OI/H), *Gomphonema acuminatum* (OI), *Cryophytes* spores	Lacustrine
670	*Fragilaria pinnata* (OI), *Fragilaria construens* (OI), *Aulacoseira sp.* (OI/H), *Cyclotella sp.* (OI?), *Navicula rhynchocephala* (OI), *Gomphonema acuminatum* (OI), *Tabellaria flocculosa* (H), *Pinnularia interrupta* (OI), *Anomoeoneis vitrea* (OI), *Epithemia sorex* (OI), *Cryophytes* spores	Lacustrine
675	*Fragilaria pinnata* (OI), *Fragilaria construens* (OI), *Aulacoseira sp.* (OI/H), *Cyclotella sp.* (OI?), *Navicula rhynchocephala* (OI), *Gomphonema acuminatum* (OI), *Tabellaria flocculosa* (H), *Pinnularia interrupta* (OI), *Cryophytes* spores	Lacustrine
678	*Navicula rhynchocephala* (OI), *Fragilaria virescens* (H), *Mastogloia cf. smithii* (M), *Tabellaria flocculosa* (H), *Navicula pygmaea* (M), *Cyclotella antiqua* (H), *Cryophytes* spores	Lacustrine/brackish
682	*Navicula pygmaea* (M), *Mastogloia exigua* (M), *Surirella cf. ovalis* (M), *Paralia sulcata* (P), *Fragilara sp.* (?), *Fragilaria virescens* (H), *Mastogloia cf. smithii* (M), *Fragilaria pinnata, Cryophytes* spores	Brackish
685	*Navicula pygmaea* (M), *Mastogloia exigua* (M), *Surirella cf. ovalis* (M), *Cymbella minuta* (OI),	Brackish
690	*Navicula pygmaea* (M), *Paralia sulcata* (P); *Mastogloia exigua* (M), *Surirella cf. ovalis* (M), *Mastogloia cf. elliptica* (M), *Fragilaria sp.* (?), *Fragilaria virescens* (H), *Cryophytes* spores	Brackish
695	*Navicula pygmaea* (M), *Paralia sulcata* (P), *Diploneis didyma* (M), *Cocconeis scutellum* (P), *Pinnularia quadratarea* (P), *Navicula directa* (P), *Surirella cf. ovalis* (M)	Brackish/marine
700	*Navicula pygmaea* (M), *Paralia sulcata* (P), *Diploneis didyma* (M), *Cocconeis scutellum* (P)	Brackish/marine
720	*Paralia sulcata* (P), *Navicula pygmaea* (M), *Cocconeis scutellum* (P), *Pinnularia quadratarea* (P), *Trachyneis aspera* (P)	Marine

Table 2. Results from the diatom check, Lake 6 Lillerundvatnet

Depth (cm)	**Indicator diatoms**	**Basin environment**
310	*Tabellaria fenestrate* (H), *Tabellaria flocculosa* (H), *Pinnularia interrupta* (OI), *Epithemia sorex* (OI), *Fragilaria pinnata* (OI), *Navicula rhynchocephala* (OI), *Cyclotella sp.* (OI?), *Anomoeoneis vitrea* (OI), *Frustulia rhomboides* (H), *Cryophytes* spores	Lacustrine
330	*Fragilaria pinnata* (OI), *Cymbella minuta* (OI), *Navicula rhynchocephala* (OI), *Anomoeoneis vitrea* (OI), *Mastogloia cf. elliptica* (M), *Pinnularia interrupta* (OI), *Fragilaria virescens* (H), *Navicula pygmaea* (M), *Gomphonema acuminatum* (OI), *Cryophytes* spores	Lacustrine, with some brackish input
350	*Fragilaria sp.* (?), *Pinnularia interrupta* (OI), *Fragilaria pinnata* (OI), *Cyclotella sp* (OI), *Anomoeoneis vitrea* (OI), *Tabellaria flocculosa* (H), *Navicula pygmaea* (M), *Surirella ovalis* (M), *Navicula rhynchocephala* (OI) *Mastogloia exigua* (M), *Cryophytes* spores	Lacustrine, with some brackish input
370	*Navicula pygmaea* (M), *Paralia sulcata* (P), *Mastogloia cf. elliptica* (M), *Surirella cf. ovalis* (M), *Fragilaria sp.* (?), *Anomoeoneis vitrea* (OI), *Tabellaria fenestrata* (H), *Tabellaria flocculosa* (H), *Cryophytes* spores	Brackish, with some lacustrine input
375	*Paralia sulcata* (P), *Navicula pygmaea* (M), *Mastogloia cf. elliptica* (M), *Surirella cf. ovalis* (M), *Fragilaria sp.* (?), *Pinnularia quadratarea* (P), *Tabellaria fenestrata* (H), *Cryophytes* spores	Brackish/marine with lacustrine input
380	*Paralia sulcata* (P), *Navicula pygmaea* (M), *Mastogloia cf. elliptica* (M), *Surirella cf. ovalis* (M), *Fragilaria sp.* (?), *Tabellaria fenestrata* (H), *Cryophytes* spores	Brackish/marine with lacustrine input
390	*Paralia sulcata* (P), *Navicula pygmaea* (M), *Mastogloia cf. elliptica* (M), *Cocconeis scutellum* (P), *Surirella cf. ovalis* (M), *Fragilaria sp.* (?), *Pinnularia quadratarea* (P), *Thalassiosira sp* (P), *Tabellaria fenestrata* (H), *Cryophytes* spores	Brackish/marine with lacustrine input
397	*Paralia sulcata* (P), *Navicula pygmaea* (M), *Mastogloia cf. elliptica* (M), *Cocconeis scutellum* (P), *Surirella cf. ovalis* (M), *Fragilaria sp.* (?), *Pinnularia quadratarea* (P), *Thalassiosira sp* (P), *Cryophytes* spores	Brackish/marine with lacustrine input
405	*Paralia sulcata* (P), *Navicula pygmaea* (M), *Mastogloia cf. elliptica* (M), *Cocconeis scutellum* (P), *Surirella cf. ovalis* (M), *Fragilaria sp.* (?), *Pinnularia quadratarea* (P) *Cryophytes* spores	Brackish/marine with lacustrine input
415	*Paralia sulcata* (P), *Fragilaria sp.* (?), *Tabellaria fenestrate* (H), *Navicula elegans* (M), *Cocconeis scutellum* (P), *Mastogloia cf. elliptica* (M), *Surirella cf. ovalis* (M), *Cryophytes* spores	Brackish/marine with lacustrine input

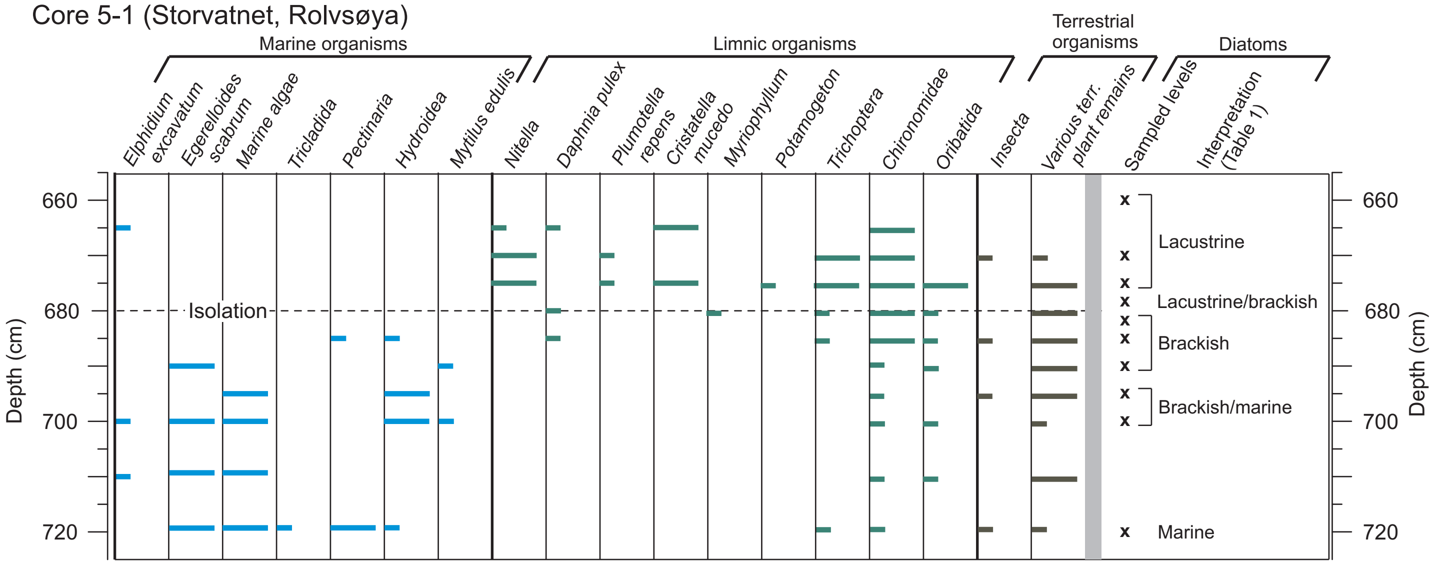

Fig. 1: Modified macrofossil diagram and interpretation of environments based on the diatom record for Lake 5, Rolvsøya.

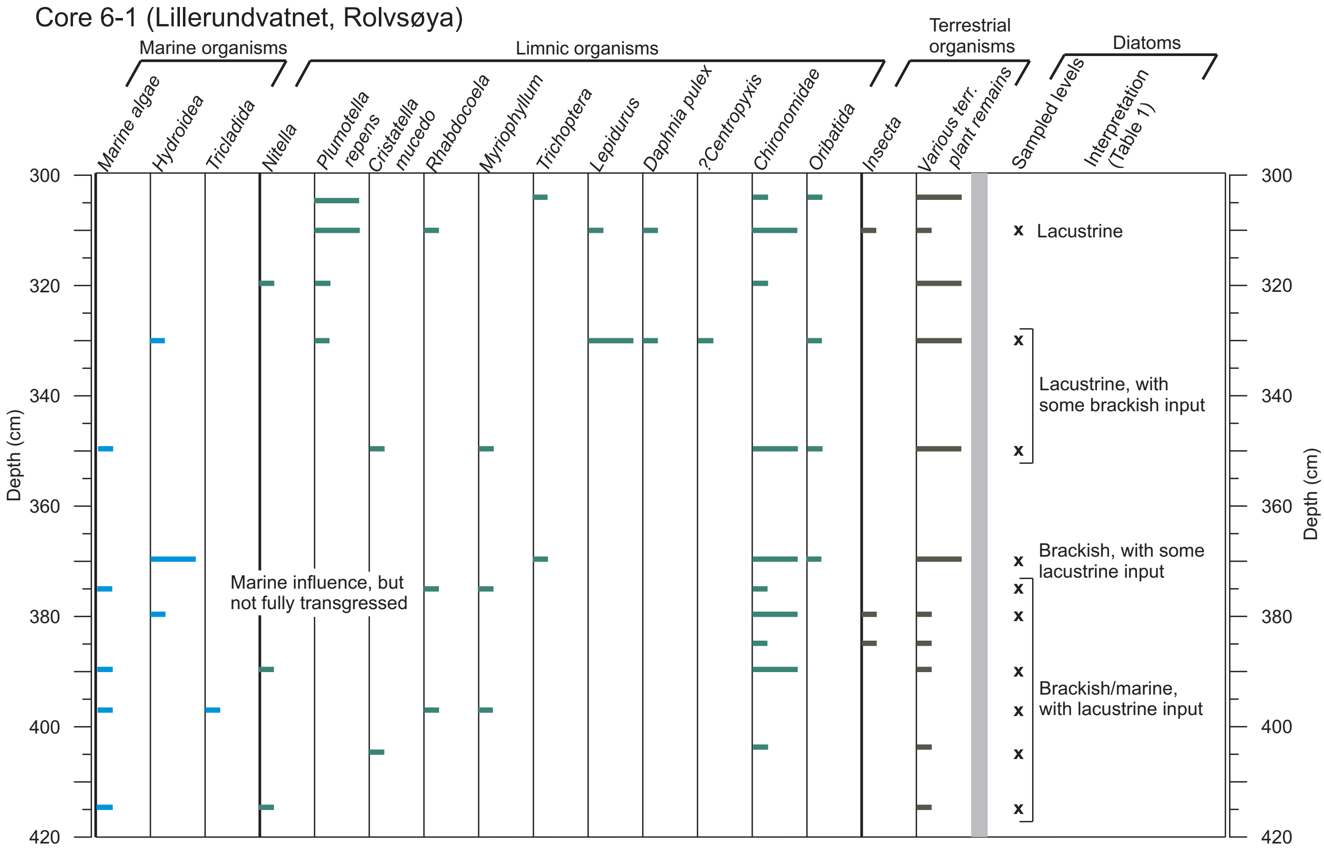

Fig. 2: Modified macrofossil diagram and interpretation of environments based on the diatom record for Lake 6, Rolvsøya

Paper I

Romundset, A., Lohne, Ø.S., Mangerud J. & Svendsen, J.I. 2010.

The first Holocene relative sea-level curve from the middle part of Hardangerfjorden, western Norway. Boreas, Vol. 39, pp. 87-104.

Paper II

Romundset, A., Bondevik, S. & Bennike, O.

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Paper III

Romundset, A. & Bondevik, S.

Propagation of the Storegga tsunami into ice-free lakes along the southern shores of the Barents Sea. Manuscript to be submitted as rapid communication to Journal of Quaternary Science.

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