CHAPTER 2

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Shoreline displacement at Ørland since 6000 cal. yr BP

ABSTRACT

A new reconstruction of the shoreline displacement at and near Ørlandet has been developed. Sediment core samples were collected from four lake basins that have been raised above sea level in the past as a result of land upheaval. Analysis of the lake sediments yields new chronological information on the relative sea level changes during the last 6000 years. The investigated lake basins are located close to the excavation site at Ørlandet, at the same uplift isobase but at different elevations. Isolation boundaries in the sedimentary records, i.e. the stratigraphic level representing the last incursion of marine water into the basins, were pinpointed using analysis of macroscopic remains of plants and animals. Terrestrial plant material for radiocarbon dating was picked from several levels across each determined isolation boundary. In addition, pumice recovered from beach sediments at the excavation site was geochemically correlated to the Katla volcanic complex in Iceland. The age of the pumice is estimated to be 3200-3400 years old and represents a maximum-limiting age for the 11 m above sea level (asl.) shoreline. Collectively, the results document a continuous regression of the sea through the period, with a possible acceleration in the rate of relative sea level fall around 2000 cal yr BP.

INTRODUCTION

The study of shoreline displacement, i.e. changes in the elevation of the shoreline position through time, has a long tradition in Nordic geology. Shoreline displacement results from the combined effects of changes in land level (isostasy) and sea level (eustasy), see Figure 1. The field is crucial to Quaternary and glacial geology and for understanding coastal landscape changes since the last ice age. Knowledge of relative sea level changes in the past is also important to studies of present-day sea level change, including prospects for the future in light of human-induced climate change. In order to understand how multiple interrelated processes affect dynamic changes in nature today, detailed knowledge of past changes is vital.

Geological data regarding shoreline displacement is also widely used in the field of archaeology to constrain the the time-span of of coastal/near-coastal archaeological sites. Shoreline displacement is thus an important dating tool in coastal archaeology, especially in glacio-isostatically uplifted regions like Scandinavia. However, due to large spatial differences in crustal uplift, the development of a

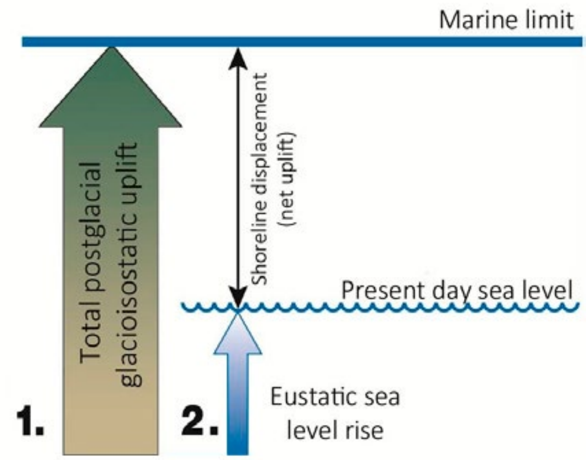

Figure 1. Shoreline displacement (black arrow) at a typical locality on the Norwegian coastline is the sum of total land rise (thickest arrow) and sea level rise (blue, thinner arrow). Marine limit (the highest shoreline since deglaciation) and the present sea level/shoreline are also marked. Illustration by Harald Sveian, NGU.

shoreline through time will vary from site to site, and may be significantly different at sites separated by only a few km. The accuracy of archaeological dating by means of ancient shorelines, therefore, fully depends on how well the geological history of shoreline displacement has been mapped, locally as well as regionally.

In August 2015, the Geological Survey of Norway (NGU) was contacted regarding the possibility of improving the knowledge of shoreline displacement at Ørlandet. Anders Romundset (geologist, NGU) led the project, following much previous research into postglacial relative sea-level change in various parts of Norway (Romundset et al. 2010; Romundset et al. 2011; Romundset et al. 2015; Romundset et al. 2018); NGU has both the expertise and relevant field and laboratory equipment for undertaking studies of past shoreline changes.

The excavation area is located at approximately 11 m asl. NGU, therefore, focused on improving the reconstruction of shoreline displacement for elevations below ca. 20 m asl. in order to cover the relevant period. Based on existing knowledge (Kjemperud 1986), shorelines from these elevations are late Holocene in age. A detailed evaluation of existing data, including isobase reconstructions, as well as a survey of topographical and geological maps, resulted in the identification of four potential isolation basins at relevant elevations. Environmental conditions such as topography, landscape, and the nature and distribution of surficial deposits are important variables affecting the potential to reconstruct shoreline displacement in an area.

MATERIAL AND METHODS

Background and previous work

The existing knowledge of postglacial shoreline displacement in coastal Trøndelag, especially the chronology, stems largely from a doctoral thesis from the 1980s (Kjemperud 1982; Kjemperud 1986). A large amount of field data was gathered during this research, and this has resulted in the shoreline displacement since deglaciation (c. 12-14.000 cal yr BP) in this region being relatively well known (Figure 2). Some of the field data was also collected from the areas of Bjugn and Ørlandet, implying that the reconstruction is largely valid for this area. Based on this previous work, it can be assumed that the shoreline fell below 11 m asl. about 3000 years ago. However, this assumption is uncertain since the shoreline development through this time period is based on only a single isolation basin record, Eidsvatnet in Bjugn (Kjemperud 1982). The objective of the current study was to, therefore, gather more data for late Holocene shoreline changes at Ørlandet, with an emphasis on improving knowledge of the rates of relative sea-level changes.

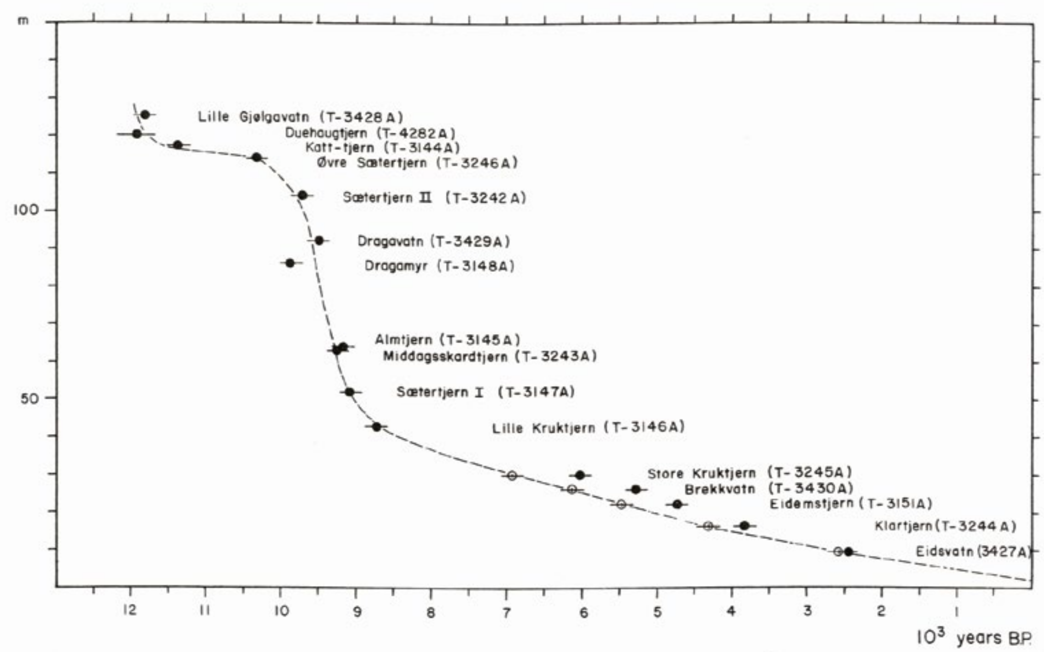

Figure 2. The pre-existing shoreline displacement curve from Kjemperud (1986). Note that the development through the last four thousand years is based solely on one basin isolation with a single bulk sediment radiocarbon age.

Isolation basins and coring equipment

In this study we used so-called isolation basins to make a detailed reconstruction of the shoreline displacement at Ørlandet. The method has been used extensively in Norway because the landscape in many coastal regions contains numerous widespread peat bogs, ponds and small lakes which are ideally suited for this methodology.

Geological records from isolation basins are unique sea level archives. By sampling (i.e. coring) and analyzing the stratigraphy from multiple basins, it is commonly possible to reconstruct past relative sea level changes with high precision (Figure 3). Isolation basins are essentially depressions in bedrock (often produced by glacial erosion) which have been uplifted above sea level during postglacial land emergence. The basins are, therefore, only located below marine limit, and record the transition from marine to lacustrine depositional environments. In Norway, marine limit varies from only a few meters asl. to more than 200 m asl., depending on the amount of glacio-isostatic depression (the thickness of the ice sheet) during the last glaciation. At Ørlandet, marine limit is probably situated close to 140 m asl. By radiocarbon dating the transition from marine to lacustrine facies in sediment cores collected from the basins, it is possible to discern precisely when various basins became disconnected from the sea, and also whether the basins at some point were submerged during transgressions. More information on the isolation basin method may be found in Romundset (2010) and Long et al. (2011).

The surficial geology in Ørlandet consists of thick till deposits, possibly representing an ice-marginal position during the early stages of the last deglaciation. The till is in most places covered by marine

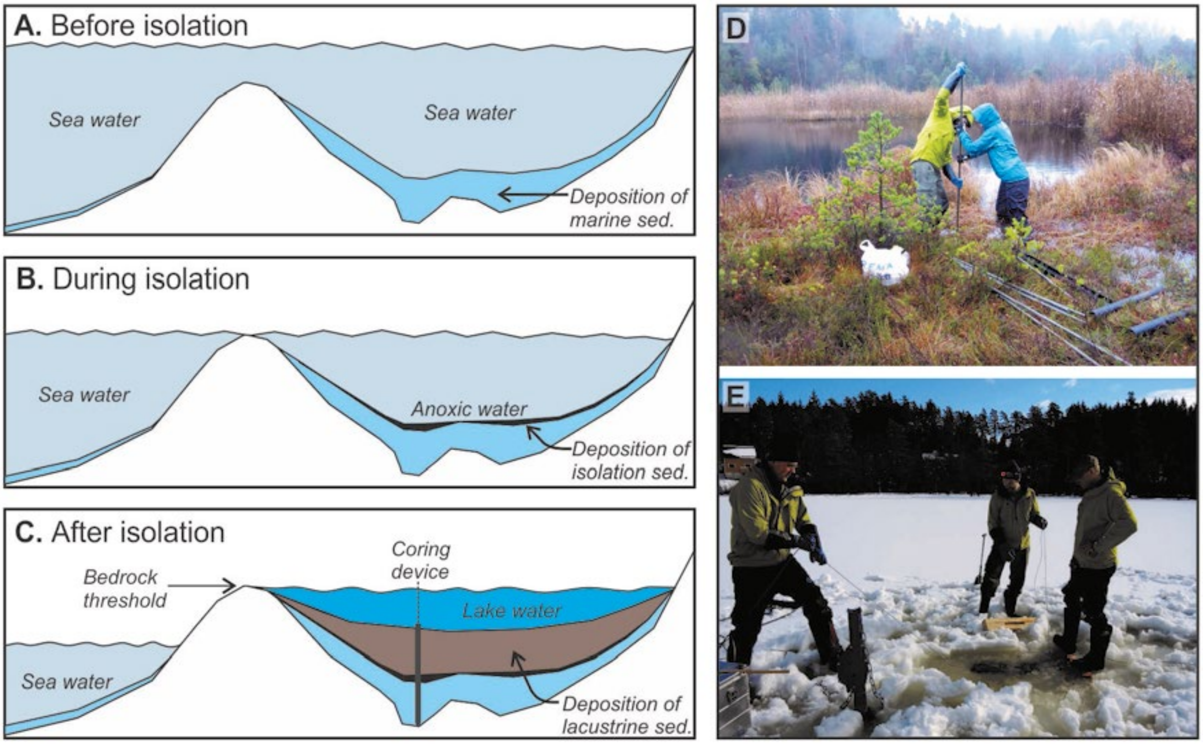

Figure 3. The principle of the isolation basin method. Left (A-C). a theoretical transect perpendicular to the coastline, with a small basin situated near the sea. A. the situation just after deglaciation, with the shoreline at marine limit, well above the basin threshold. Marine sediments (silt, clay and remains of marine biota, e.g. mollusk shells) are deposited. B. the shoreline has been lowered and salt sea enters the basin across the threshold during high tide, twice a month. During a relatively brief period the basin environment is brackish, with depleted salinity. Black, finely layered sediments are deposited on the lake floor, with almost no remains from living organisms (i.e. subfossil parts of animals and plants). C. the basin is long since isolated. Brownish gyttja (a typical lake sediment) is deposited. The vertical line illustrates how a core sample will penetrate the sedimentary sequence and retrieve deposits from the geological archive. D. Field photo of coring with a Russian corer from the rim of a lake. E. Field photo of piston coring at a frozen lake in wintertime.

sediments of varying thickness. Along most of the present coastline of Ørlandet there is abundant beach gravel near the surface. The beach gravel was deposited during postglacial regression that gradually exposed the former seabed. Since Ørlandet consists mainly of these surficial deposits, the landscape is not well-suited for isolation basin studies. However, by surveying areas located near the same uplift isobase, north and south of Ørlandet, we found four basins that we assume do not significantly deviate from Ørlandet with regard to past uplift rates, at least not for the late Holocene. We found basins in Bjugn (Eidsvatnet, also investigated by Kjemperud) and in Vassbygda/Agdenes (low-lying Storvatnet, Litjvatnet, and the higher Eidemstjønna – which was also investigated by Kjemperud).

Except for Litjvatnet, we used a modified piston coring apparatus to sample the lake sediments during January-March 2016 from frozen lake ice surfaces. A standard 110 mm diameter PVC-tube, with a piston mounted in its lower end, was attached to a cable and lowered to the lake floor. A second cable was attached to the piston and secured on the lake ice surface. A third cable was fastened to a weight (25 kg) that was used to strike the top of the coring apparatus repeatedly (up to several thousand times), thus hammering the PVC-tube slowly downwards into the sediments. Upon recovery, all sediment was captured in the sample tube as a result of the locked piston, which provided suction and prevented the sediment from sliding out the bottom of the tube. This type of piston corer may retrieve up to 6 m-long core samples of 110 mm diameter, and can be used in water depths of 100 m or more. The piston corer provides long, continuous sequences, but the operation is time-consuming and involves much work with equipment and transportation. Frozen lakes are a great advantage to the work, compared to using a floating raft. One full work day is normally needed for coring one lake basin.

The Litjvatnet basin is shallow and was therefore sampled using a so-called Russian peat corer (Jowsey 1966), i.e. one-meter long samplers of various diameters, attached to rods. The corer was lowered to desired sampling depths, and rotated 180 degrees to capture sediment within the closed sampler. One meter-long samples were raised to the surface without being disturbed and collected for subsequent analysis. Sampling with a Russian peat corer is logistically much easier than piston coring and requires less time. Recovered samples constitute half-cylinders, the volume of which depends on the diameter of the sampler used (i.e. 5–11cm). Smaller samplers are more easily lowered through the sediment and this means they can penetrate deeper through deeper stratigraphy, including sand layers and wood. Conversely, smaller samplers may yield insufficient amounts of sample material and plant material from certain depths for radiocarbon dating.

Laboratory work – sediment analysis and radiocarbon dating

In this study, macrofossil analysis was used to identify changes in the basin environment through time. Macrofossils are sub-fossil remains of plants or animals (>150μm). This method is replacing diatom analysis, which has traditionally been the more commonly used proxy for detecting salinity changes in basin environments. Many common plant and animal species live in either fresh or saltwater, and some prefer brackish conditions. Salinity changes affect the species assemblage of the basin environment. Remains of dead organisms sink to the lake floor and become part of the lake sediment. While soft tissue generally decays rapidly, some harder, more resistant parts are preserved in the sediment. The macrofossils recovered from sediment cores of isolation basins (i.e. the biostratigraphy) will therefore record the environmental changes that took place when the basin became disconnected from the sea during land emergence and isolation. Reworking and transport by wind and/or sea spray may be a problem for microfossil records (diatoms and pollen), but these processes do not generally affect larger macrofossils. The stratigraphic level marking the transition from marine/brackish to limnic species is interpreted to represent the last incursion of saltwater into the basin across the basin threshold during highest astronomical tide. Thus, it is important to note that the elevation represents high tide and not mean sea level. Most shoreline displacement curves represent mean sea level and the basin elevations therefore need to be adjusted for the local tidal difference.

The ages of the stratigraphic boundaries were determined by radiocarbon dating of macrofossils. A common problem in late Pleistocene-Holocene palaeoenvironmental studies has been the errors associated with radiocarbon dating of bulk sediment samples. This methodology commonly involved cutting several cm-thick slices of sediments from the core sample, (cf. Kjemperud 1986), and using all the material therein for radiocarbon analysis. This technique, therefore, often resulted in the inclusion of minerogenic carbon in the dated sample; as well as reservoir effects and/or reworked material that could influence the measured radiocarbon age. Today, these problems are avoided by use of AMS-dating of selected terrestrial plant macrofossils, which allows dating of small samples (less than 10 mg) with high precision. Typical material that was dated in this study includes leaves from trees or bushes, small twigs, pine needles, and other terrestrial material that was large enough to be identified. Where possible, we obtained multiple radiocarbon dates from material collected from several levels (at least three) spanning the isolation boundary/event, to ensure a robust chronology.

Pumice at Ørlandet

The elevation of pumice (11 m asl.) discovered at Ørlandet and its occurrence on a raised shoreline allow its approximate age to be determined on the basis of a previously published relative sea-level curve (Kjemperud, 1986). While rates of late Holocene RSL change are not well-constrained for this region, the pumice was most likely deposited between 2000 and 4000 calibrated years before present. To determine the age of the pumice more precisely, we attempted to correlate the pumice to known late Holocene Icelandic volcanic eruptions. Specifically, we used electron probe microanalyses to determine the major element composition of two pumice sample-sets – one from Ørlandet and another from Kobbvika at the island of Averøya (Table 1), as well as of eight tephras from the Katla volcanic complex on Iceland (which has previously been correlated to Norwegian pumice; (Table 2; Newton 1999)). Major element composition of the pumice and tephras was determined using a Cameca SX100 electron probe microanalyzer at the Department of Geosciences, University of Edinburgh. Each sample was analyzed 10-20 times in the electron probe microanalyzer and the data is presented in Table 3.

RESULTS

A thorough survey of existing maps, aerial photos and digital elevation models was first conducted in order to identify potential isolation basins located at the relevant elevations (below c. 20 m asl.). All of the prospective basins are situated on or near the same isobase, thus avoiding the effects of (unknown) differential land uplift. The distance between basins may still be quite large, however, given that their distribution follows the isobase direction. A few apparently deep bogs were found in the eastern part of Ørlandet, in addition to the large lake Eidsvatnet in Bjugn (Figure 4). In addition, some relevant lakes in Vassbygda, Agdenes, on the opposite side of Trondheimsfjord, were found and are situated on the same isobase as Eidsvatnet.

After initial field reconnaissance and some attempts to core the bogs at Ørlandet, including the now reconstructed Rusasetvatnet, we found that these basins were too shallow and therefore not suitable sea-level reconstructions. So we shifted our focus to larger lakes containing the desired stratigraphic record. At first, coring was done from lake ice in Agdenes in January 2016, where after several attempts we recovered a core sample from c. 16 m water depth in Storvatnet. Litjvatnet is relatively shallow and was successfully cored along several transects using the Russian peat corer, in February, 2016. Eidemstjønna is deeper and here we collected three piston cores.

Laboratory analyses of the collected core samples were carried out at NGU during the months following fieldwork in spring, 2016. The main task was to identify biostratigraphical boundaries representing

Figure 4. Map of the field area. Basins are numbered as follows. 1. Eidemstjønna, 2. Eidsvatnet, 3. Storvatnet and 4. Litjvatnet. The white stippled lines mark the shoreline isobase direction which is near coast-parallel. Isobases are theoretical lines that cross areas that experienced similar amounts of shoreline displacement since the last deglaciation.

the time when the basins were uplifted above contemporary sea level. Identification and preparation of selected radiocarbon dating samples (terrestrial plant remains) was carried out at NGU, whereas the AMS measurement was performed at Poznan Radiocarbon Laboratory, Poznan, Poland. Multiple samples from different levels near each isolation boundary were dated in order to gain a robust chronology of basin isolation events.

Basin 1 – Eidemstjønna

We cored at three different sites in the middle of this lake and from each site we recovered a c. 4 m long core. The sequence comprises marine sand in the lower part, with increasing amounts of shells fragments, followed by ca. 2 m of pure shell sand and gyttja on top. The sudden transition from a high-energy deposit (shell sand) to gyttja suggests there is a hiatus in the record, which unfortunately

Figure 5. A section of the cored sequence from Eidemstjønna, showing the shell sand and the abrupt transition to gyttja above. Up is toward the left.

makes it a poorly developed sequence, not suitable for a precise sea-level determination (Figure 5). This is probably a result of conditions at the basin threshold, where thick beach gravel deposits dam the lake. Dating the gyttja would at best yield a minimum age for the palaeo-sea level and would not improve the precision of the existing reconstruction. No further analysis was therefore carried out on the record from Eidemstjønna.

Basin 2 – Eidsvatnet

The elevation of Eidsvatnet (the lake surface) is reported on topographic maps as 10 m asl., but the actual elevation is about 8 m asl. Distinct traces of a former lake shoreline can be seen as an abrasion notch at about 12 m asl. visible around much of the lake (Figure 6). It is known that the lake level was lowered twice, most recently in AD 1948 by ca. 120cm. The outlet stream is deeply incised into beach deposits (shell-bearing gravel and rocks). The deposits are massive and are located in a sheltered location with regard to waves, so there is little risk that significant incision of the threshold took place after the lake had become isolated. Man-made channelizing in modern times caused the lowering. Based on these observations, we place the original lake elevation at ca. 10 m asl. (+/- 0.5 m) before humans impacted the threshold.

The depth of the lake floor was mapped along several transects in the southern (deeper) part of the lake. A larger and flat-bottomed area of ca. 50x100 m below the hill Ørnklumpen was found to be the deepest at ca. 8.5 m depth. We cored in this area (Figure 6), which is probably different from where Kjemperud recovered his sample, since he gives a water depth of 4.9 m. Usually, the best location

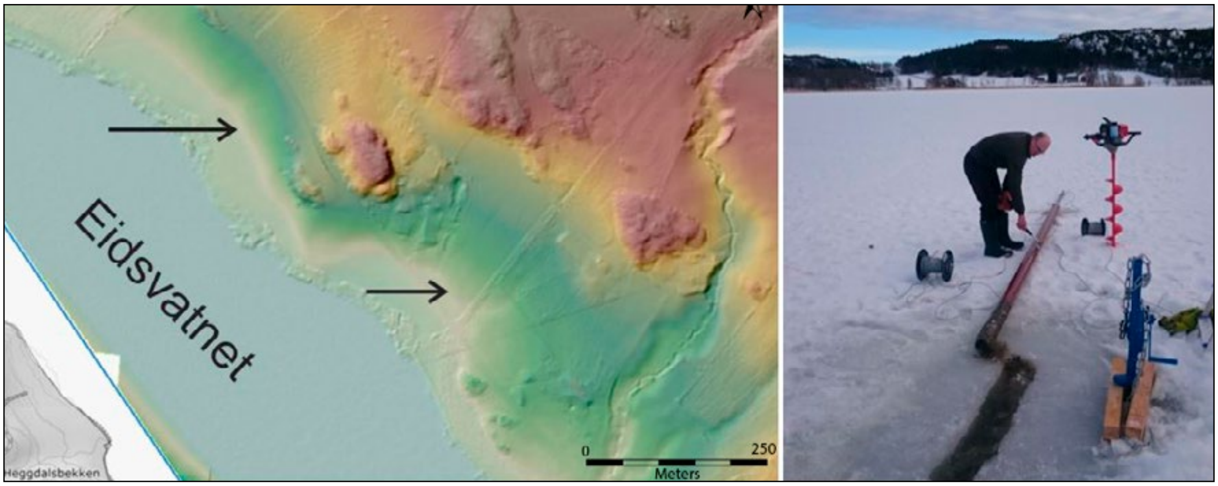

Figure 6. Left. elevation model of the terrain near Eidsvatnet. The black arrows mark an older shoreline (abrasion notch) at ca. 12 m asl. It represents an older, original elevation of the lake at near 10 m asl. Right. From field work. The core sample has been lifted and placed on the lake ice.

for coring is the deepest and flattest area of the lake floor. This provides little risk of disturbance by potential mass movements, thereby giving the best chance of recovering a complete, uninterrupted sedimentary sequence.

The core sample from Eidvatnet comprised a well-developed and undisturbed isolation sequence. The transition to a lake environment is well defined at 903 cm depth (below the lake surface) and has been dated from four samples to about 2300-2200 cal years BP. This is about 400 years younger than Kjemperud's result, and thereby a useful revision of the existing reconstruction. The four congruent radiocarbon dates from a continuous sequence give an accurate and robust age determination for this palaeo-sea level.

Basin 3 – Storvatnet

The lake surface of Storevatnet is presently ca. 4.6 m asl. It is known, however, that the lake was lowered in the 1920s by about one meter. There are also indications of an older shoreline (abrasion notch) at about 6.5 m asl. in several locations around the lake. Therefore we infer that the lake surface prior to human influence was near 6 m asl. Using an existing map of the bathymetry of Storvatnet we obtained cores from the deepest part of the lake (slightly deeper than 16 m), which had a relatively flat bottom (Figure 7).

We collected several relatively short (1-2 m) cores from Storvatnet. Collection of longer cores was prohibited by very compact and thus impenetrable deposits.. Due to low sedimentation rates in this basin, however, the short cores that were retrieved do contain the desired complete marine-lacustrine sequence. The disconnection from the sea is clearly represented by a finely laminated unit. Thin laminae of alternating black and lighter layers were deposited when the lake had a brackish/anoxic environment (Figure 8). Based on the analysis of various macrofossils, the isolation boundary was placed at 1685cm. A series of four radiocarbon dates allows for precise age determination of the isolation event to 1700-1600 cal years BP.

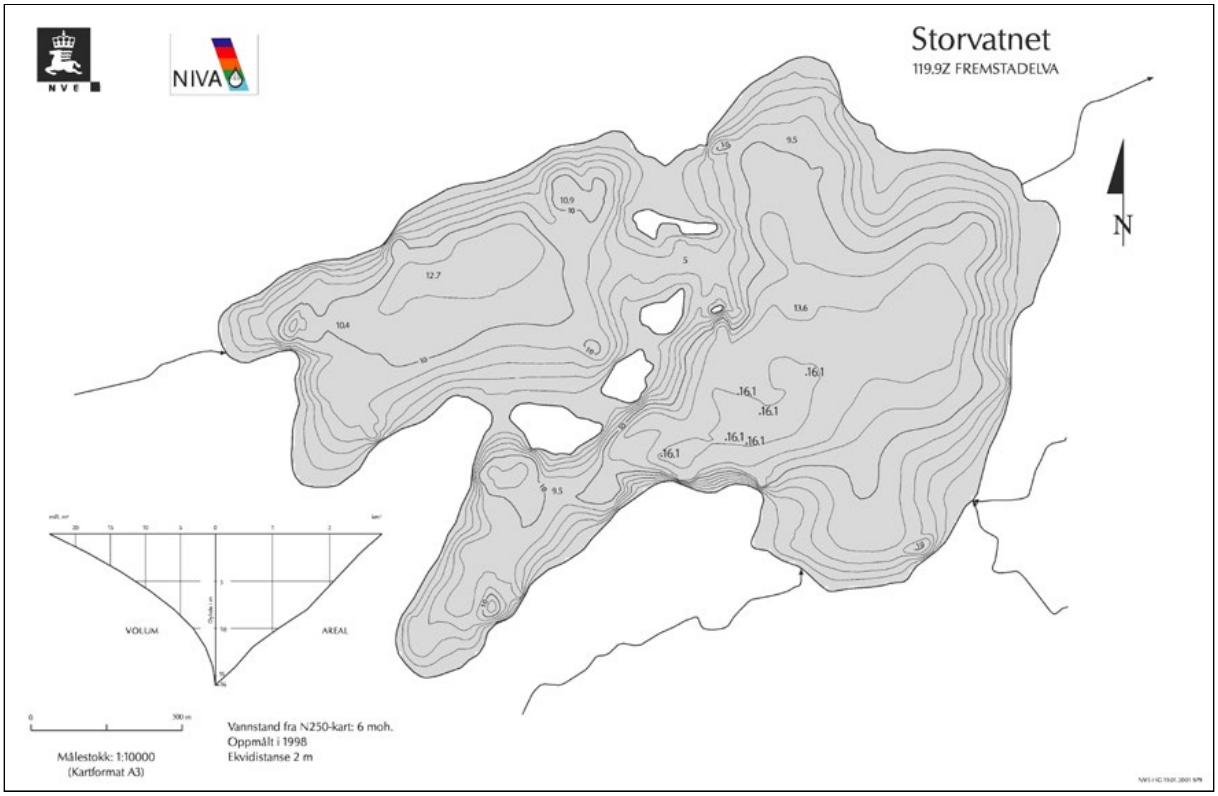

Figure 7. Bathymetric map of Storvatnet (made available by NVE). The position of the core sample in the deepest, flat-bottomed part of the lake is indicated.

Basin 4 – Litjvatnet

Litjvatnet is located next to, and downstream of Storvatnet. The threshold of Litjvatnet has been modified by humans several times, and the outlet stream, Nordgjerdelva, is today channelized. Lowering of the lake surface by about 1 m occurred in the 1920s (similar to Storvatnet). The lake level was again lowered by 50-80cm in 1962/63 when a ca. 200 m wide area in the eastern part of the lake was made dry land. The lake was leveled in 1977 to 4.03m asl. (normal high lake level), and in 1987 the outlet was cleared and the elevation was lowered again by an additional 70cm to 3.33m asl. The present lake surface is located ca. 3.7m asl. The original lake elevation is obviously uncertain, but we assume it was near 5 m asl. The dating results from this work show that the two lakes Litjvatnet and Storvatnet were separated at the time of isolation.

A bathymetric map also exists for Litjvatnet (Iversen et al.1996). The shallow depths allowed for the use of the Russian peat sampler from the frozen surface of the lake. Core samples were collected from several transects across the lake. The samples were examined in the field and facilitated a good understanding of the lateral variations of different sedimentary units. (Figure 9).

The isolation of Litjvatnet is well defined at 498cm depth and was dated using samples from two different core sites. Multiple macrofossil samples from levels spanning the isolation boundary were dated from

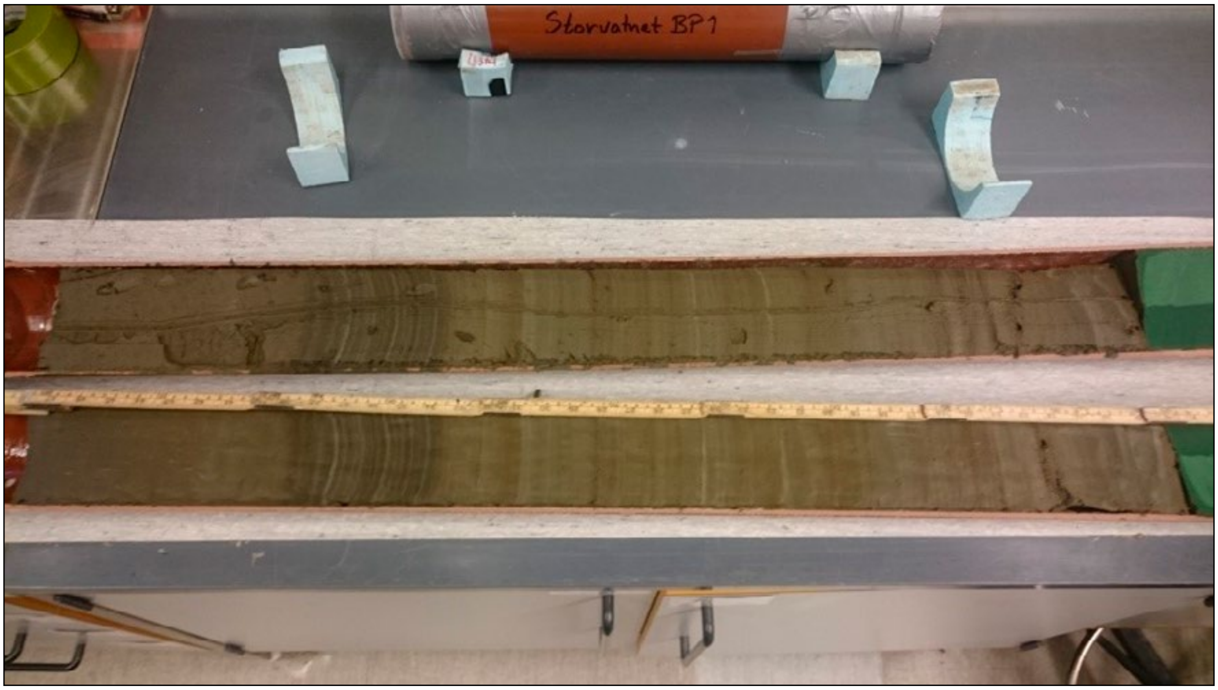

Figure 8. A section of the cored sequence from Storvatnet, with the isolation from the sea represented by thin, black-colored laminations. Up is toward the left.

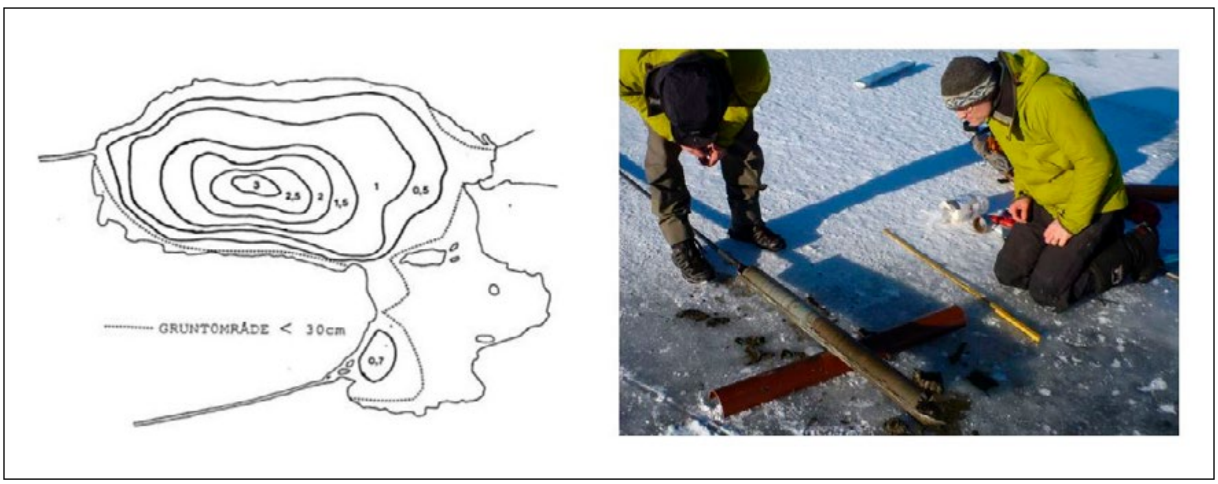

Figure 9. Left. Depth contours of Litjvatnet (Iversen 1996). The lake was cored along several transects, whereas the analysis and dating was done on a core sample from the deepest part. Right. A half-cylinder core sample from Litjvatnet is opened on the spot and documented in the field.

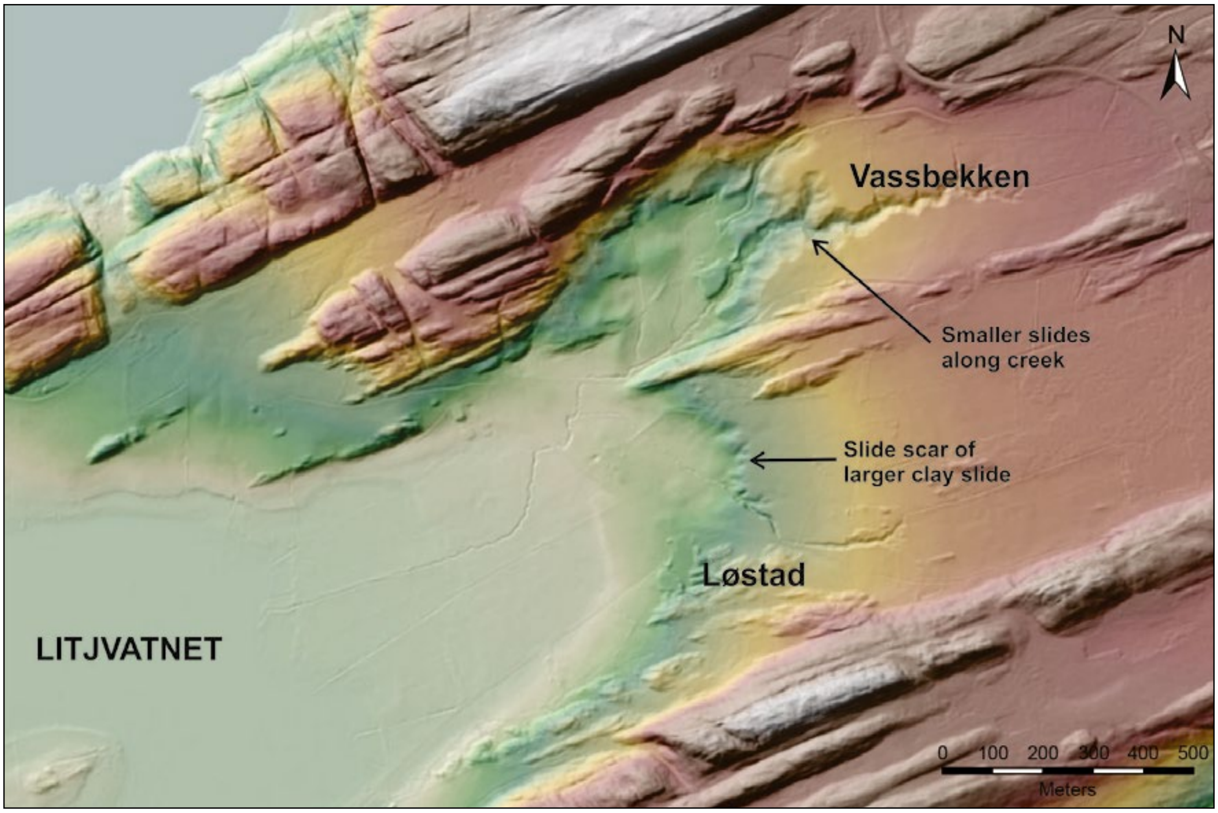

Figure 10. Terrain model of the area northeast of Litjvatnet. The colors indicate elevations. Arrows show likely source areas for clay slides. See text for details.

both core sites. Based on the results, we conclude that the isolation took place 1600-1400 cal years BP, i.e. a short time after Storvatnet. Nonetheless, the radiocarbon dating results from the two lakes, do yield statistically significant different ages for the two lake isolation events.

Clay slide near Litjvatnet

An additional result from coring Litjvatnet was the discovery of a ca. 30cm thick, light-grey colored deposit of clay and silt, stratigraphically located about 10cm above the isolation boundary. The unit was found at all core sites and had similar character and thickness across the lake. Sedimentological analysis demonstrates that the layer was deposited in a lacustrine environment. We believe the layer was deposited following a slide of uplifted marine clays that are found within the lake catchment. The lack of similar deposits in the record of Storvatnet suggests that the slide happened locally. A laser-scan terrain model of the area (Figure 10) shows possible slide scars associated with the deposit, northeast of the lake. There are indications of slide scars both near Løstad and along the stream Vassbekken. Based on the radiocarbon dates from the lake record, the slide most likely took place about 1000 cal years BP.

Depth below surface (cm)	Sample name	Purpose/ strati-graphic level	Calibrated age (a BP, 2σ)	Weighted average (μ)	Material dated	Sample weight (mg)	Laboratory number	Radiocarbon age (a BP)
Litjvatnet, Agdenes. Insert coordinates. Isolation boundary determined at 498 cm depth.								
411	OR-1-1-1	Laminated unit	270-20	130	Bulrush stalk	29	Poz-86903	90 ± 30 BP
490	OR-1-1-2	Isolation (above)	1700-1520	1590	Mosses	5	Poz-86904	1680 ± 30 BP
490	OR-1-1-3	Isolation (above)	1320-1180	1260	Terrestrial leaf fragments	24	Poz-86905	1340 ± 40 BP
490	OR-1-1-4	Isolation (above)	1350-1260	1300	Plant stalks, a twig	18	Poz-86906	1375 ± 30 BP
490	OR-1-1-5	Isolation (above)	1390-1290	1340	A single stalk	8	Poz-86907	1450 ± 30 BP
510	OR-1-1-6	Isolation (below)	1820-1620	1730	Wood	7	Poz-86908	1800 ± 30 BP
517	OR-1-1-7	Isolation (below)	1720-1560	1650	Large twig	404	Poz-86909	1740 ± 30 BP
500-502	OR-1-2-1	Isolation (just below)	1810-1560	1670	Twig with unharmed cortex	37	Poz-86910	1760 ± 40 BP
502-503	OR-1-2-2	Isolation (below)	2040-1880	1950	Stalks	21	Poz-86911	2005 ± 30 BP
503-504	OR-1-2-3	Isolation (below)	2000-1870	1930	Stalks and mosses	17	Poz-86913	1980 ± 30 BP
498-500	OR-1-3-1	Isolation (just below)	1950-1810	1880	Potamogeton fruits	33	Poz-86889	1930 ± 30 BP
504	OR-1-3-2	Isolation (below)	1830-1620	1740	Small Ericaceae twig with buds	7	Poz-86890	1805 ± 30 BP
Storvatnet, Agdenes. Insert coordinates. Isolation boundary determined at 1685 cm depth.								
1631	OR-2-1	Top of core sample	430-modern	230	Stalk	22	Poz-86893	235 ± 30 BP
1631	OR-2-2	Top of core sample	290-modern	140	A single Pinus cone	80	Poz-86894	140 ± 30 BP
1671-1672	OR-2-3	Isolation (above)	1400-1300	1350	Terrestrial leaf fragments	19	Poz-86895	1460 ± 30 BP
1673-1675	OR-2-4	Isolation (above)	1550-1400	1470	Seeds, stem fragment	21	Poz-86896	1590 ± 30 BP
1683-1685	OR-2-5	Isolation	1730-1560	1660	Conifer needle, Betula seeds (N>50) and leaf fragments	7	Poz-86897	1750 ± 30 BP
1693	OR-2-6	Isolation (below)	2000-1870	1930	One single leaf	12	Poz-86899	1980 ± 30 BP
Eidsvatnet, Bjugn. Insert coordinates. Isolation boundary determined at 903 cm depth.								
838-839	OR-3-1	Top of core sample	modern		A single stalk	7	Poz-86900	137.67 ± 0.33 pMC
838-839	OR-3-2	Top of core sample	modern		Terrestrial plant fragments	9	Poz-86901	140.44 ± 0.35 pMC
885-886	OR-3-3	Isolation (above)	1700-1540	1620	Terrestrial plant fragments	35	Poz-86867	1705 ± 30 BP
896-897	OR-3-4	Isolation (above)	2310-1990	2120	Terrestrial plant fragments	13	Poz-86868	2130 ± 40 BP
899-900	OR-3-5	Isolation	2300-2000	2110	Terrestrial plant fragments	17	Poz-86869	2125 ± 30 BP
902-903	OR-3-6	Isolation	2310-2060	2210	Betula seeds and leaf fragments	15	Poz-86870	2170 ± 30 BP

Table 1. *Radiocarbon dated samples from Litjvatnet, Storvatnet and Eidsvatnet.*

Figure 11. Pumice collected at Ørlandet, a subsample of which was sent to the University of Edinburgh for geochemical analysis.

Results for the pumice find

Abundant pumice (Figure 11) was found within a small part of the excavation area. All the pumice was situated at the same elevation, near 11 m asl. Pumice is a unique rock type produced by volcanic eruptions, containing abundant vesicles, including trapped gas bubbles, that commonly render it less dense than water. Discoveries of pumice along raised palaeo-shorelines along the Norwegian coastline are not rare, but most of the documented sites are from levels close to the mid-Holcoene Tapes transgression shoreline. The Tapes transgression led to erosion and reworking, and thereby concentrated previously deposited pumice as a lag deposit at the transgression highstand level. The elevation of the Tapes level varies largely depending on geographical location (isobase), but for Ørlandet there is little doubt given the new and existing relative sea level data that the 11 m shoreline is much lower – and thus younger. Multiple pumice samples were collected from Ørlandet and a subset of these were geochemically analysed along with a second sample-set from Kobbvika (from a similar geological setting), primarily to investigate possible correlations to known eruptions/tephras from the Icelandic Katla volcanic complex (Larsen et al. 2001).

The microprobe data contains few outliers and represents a significant improvement upon previous efforts to precisely determine the major element composition of pumice collected from raised shorelines in the North Atlantic region (Newton, 1999). Bi-plots of Fe vs. Ti and other cations illustrate that variability within the pumice data is comparable to that for the analyzed tephras. The major element composition of the pumice from Ørlandet and Kobbvika is most similar to that of the SILK-YN, MN, -LN, and -N4 tephras (Figure 12). The percentage by weight of Ti in the Ørlandet and Kobbvika pumice (when OK-P-10 is excluded) most closely matches that of SILK-MN and –LN; however, the pumice exhibits greater variance in Fe (Figure 12). Given the known late Holocene age of the pumice we propose a genetic correlation to SILK-MN or -LN, suggesting that the pumice was deposited following the Katla eruption that deposited either: i) SILK-MN at approximately 3.2 cal ka BP, ii) SILK-LN at approximately 3.4 cal ka BP, or iii) both SILK-MN and -LN. We note that SILK-LN has much less variance in Ti, which averages 1.22 +/- 0.01 and has a trendline that most closely parallels the pumice data in Fe vs. Ti plots. The current compositional data, however, prevents us making a more robust correlation to

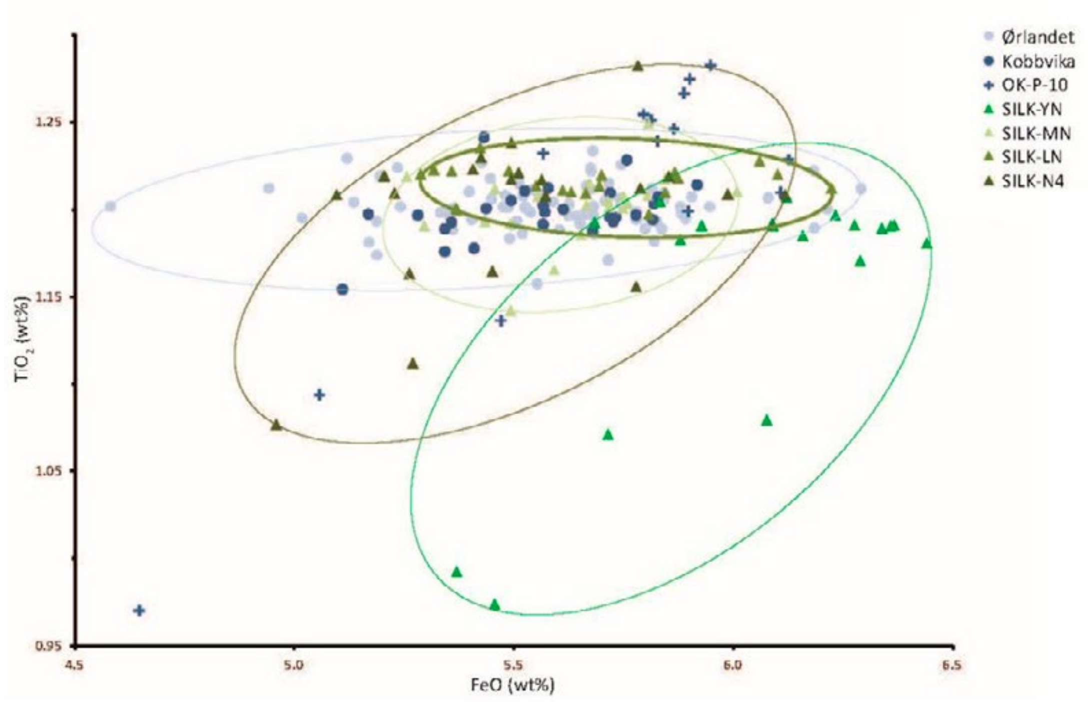

Figure 12. Plot of the composition of iron and titanium for the pumice and for relevant tephra deposits in Iceland. Ellipsoides show the distribution and overlap of measured values.

SILK-LN. Nonetheless, the pumice data provides a robust new maximum-limiting age for the 11 m asl. shoreline of c. 3.2-3.3 cal ka BP.

OK-P-10 exhibits greater variance in Ti among the pumice samples and its range of values matches most closely the data for SILK-N4 (Figure 12). It may, therefore, have been sourced from the SILK-N4 eruption ca. 3.9 cal ka BP but transported to and/or deposited along the Norwegian coast following a subsequent eruption (i.e. SILK-MN or -LN). Its occurrence within a littoral facies characterized by high concentrations of pumice indicates that its deposition was likely due to high rates of beach stranding following an Icelandic eruption, as opposed to more random redeposition from a higher shoreline during relative sea-level regression.

DISCUSSION

The revised shoreline displacement curve

The main result of the present investigation is the revised shoreline displacement curve (Figure 13), covering the period since 6000 cal years BP. The curve illustrates the development of the mean sea level through this period, and is based on new field data and the chronology obtained in this study.

Important aspects regarding the interpretation and use of the curve

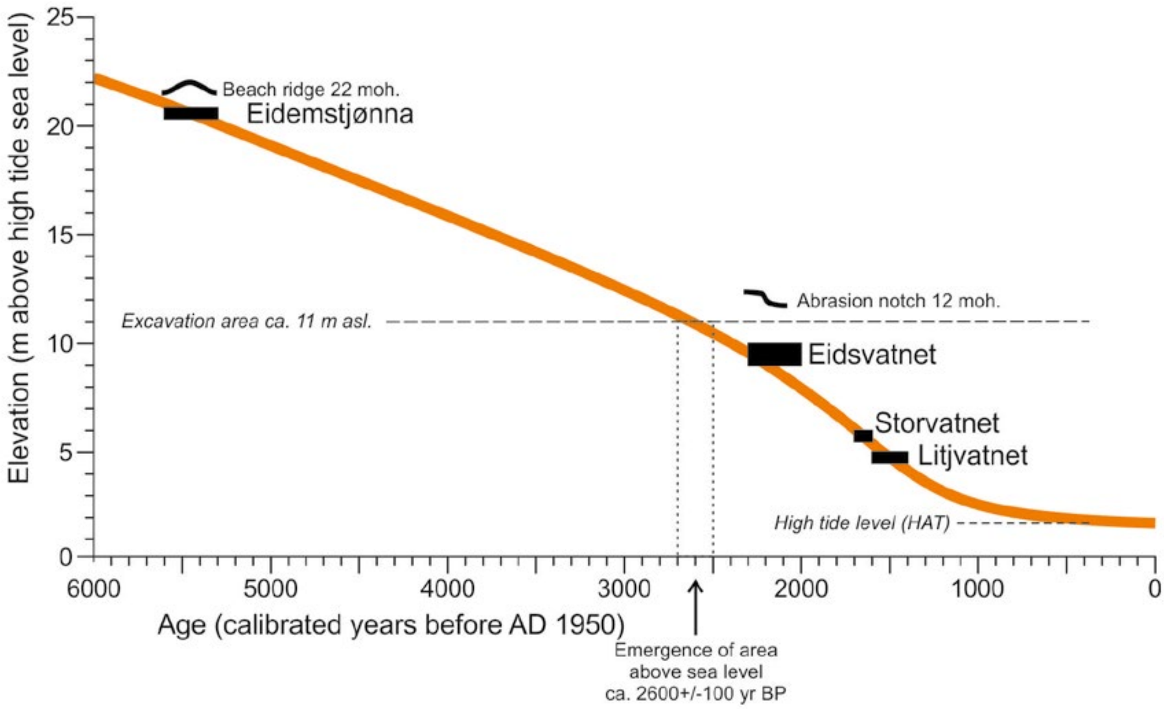

Figure 13. The new shoreline displacement curve for the period 6000 years BP to present. Note that the timescale is given in calibrated years before present, whereas Kjemperud's curve is given in radiocarbon years before present. See text for details.

- The curve is drawn as a line representing the most likely development of shoreline displacement at this isobase (running across Ørlandet). The full uncertainty envelope is not indicated on the curve, and centennial-scale deviations might be expected. The uncertainty of the reconstruction depends on the chronological accuracy of each single isolation event and possible deviations from the determined threshold elevations.

- The results show that the excavation area emerged from the sea (and high tide level) around 2600 years ago. Due to the exposed setting of Ørlandet in relation to the sea, the outer part of the area was obviously exposed to large waves, storm surges and sea spray for a while after emergence. Nonetheless, our results document that the shoreline fell relatively rapidly during the subsequent centuries. Based on the sea level curve it probably took less than 500 years before the excavation area was completely separated from the influence of storms etc.

- The shoreline displacement curve represents highest astronomical tide level. The difference between mean sea level and highest astronomical tide in Trondheim is about 180 cm. Therefore, the curve ends at this elevation for the present day.

REFERENCES

Iversen, T. H., P. Andreassen, H. Kråkvik & H. Svare 1996: *Litjvatnet Agdenes i Sør-Trøndelag*. Plantebiosenteret, Botanisk Institutt, NTNU Dragvoll.

Jowsey, P. C. 1966: An improved peat sampler. *New Phytologist* 65, 245-248.

Kjemperud, A. 1982: *Late Weichselian and Holocene shoreline displacement in parts of Trøndelag, Central Norway*. PhD thesis. Dept. of Geology, Univ. of Oslo.

Kjemperud, A. 1986: Late Weichselian and Holocene shoreline displacement in the Trondheimsfjord area, Central Norway. *Boreas* 15, 61-82.

Larsen, G., A. J. Newton, A. J. Dugmore & E. G. Vilmundardóttir 2001: Geochemistry, dispersal, volumes and chronology of Holocene silicic tephra layers from the Katla volcanic system, Iceland. *Journal of Quaternary Science* 16, 119-132.

Long, A. J., S. A. Woodroffe, D. H. Roberts & S. Dawson 2011: Isolation basins, sea-level changes and the Holocene history of the Greenland Ice Sheet. *Quaternary Science Reviews* 30, 3748-3768.

Newton, A. 1999: *Ocean-transported pumice in the North Atlantic*. PhD thesis. University of Edinburgh.

Romundset, A. 2010: *Relative sea level, deglaciation and tsunami history deduced from isolation basins*. http://munin.uit.no/handle/10037/2703. PhD thesis, University of Tromsø, Tromsø, Norway.

Romundset, A., S. Bondevik & O. Bennike 2011: Postglacial uplift and relative sea level changes in Finnmark, northern Norway. *Quaternary Science Reviews* 30, 2398-2421.

Romundset, A., O. Fredin & F. Høgaas 2015: A Holocene sea-level curve and revised isobase map based on isolation basins from near the southern tip of Norway. *Boreas* 44, 383-400.

Romundset, A., T. Lakeman & F. Høgaas 2018: Quantifying variable rates of postglacial relative sea level fall from a cluster of 24 isolation basins in southern Norway. *Quaternary Science Reviews* 197 (2018), 175-192.

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


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