3.2. POSTGLACIAL SHORELINE DISPLACEMENT IN THE TVEDESTRAND–ARENDAL AREA

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Figure 3.2.1: Part of a bedrock map covering the field area (scale 1:50,000). Crystalline rocks of the Bamble formation are found in this area. Most common are different types of granites (pink) and migmatites (yellow) (Padget 1988).

INTRODUCTION

Geological investigations as part of the archaeological project

This chapter presents an overview of the results from geological investigations that were conducted by the *Geological Survey of Norway* (NGU) as part of the archaeological excavations E18 Tvedestrand–Arendal. The main purpose of the geological work has been to document the relative sea level history of this region, where hardly any previous shoreline data exist. High magnitudes of crustal rebound in combination with complex topography have caused significant post-glacial relative sea level changes along this particular coastline. The shoreline has been lowered about 80 m during the last 12,000 years, causing an ever-changing configuration of islands, sounds and bays, particularly during the first 2000–3000 years. This, in turn, has caused changes to fishing grounds, travel routes and suitable locations for dwelling sites – changes that may well have been discernible over a single human generation.

The involvement of NGU in this project was initiated by Associate Professor Emeritus R. Sørensen at the *Norwegian University of Life Sciences* (NMBU), who has previously led similar cross-disciplinary studies (e.g. Sørensen *et al*. 2014a, 2014b). NGU started the first fieldwork with basin coring in late autumn 2014 and has conducted three subsequent field campaigns through 2015 and 2016. A. Romundset has led the work, with field assistance by F. Høgaas, T. Lakeman, L. Gislefoss and O. Fredin, all at NGU. All laboratory

Figure 3.2.2: Map of deposits correlated to the stillstand or advance of the ice front during the cold Younger Dryas chronozone (12,700–11,500 years ago). The field area is marked by the yellow asterix. Ages of regional glacial maxima in thousand years before present (modified from Hughes *et al.* 2015).

work including preparation of samples for dating was carried out by Romundset and completed at NGU following each field campaign. All the radiocarbon datings have been performed at the *Poznan Radiocarbon Laboratory* in Poland. The text and figures present a summary and short discussion of the main results, fitted to the format of this book. The complete material with all data tables etc. will be published separately in peer-reviewed geoscientific journals.

Bedrock and landscape

The excavation area between the towns of Tvedestrand and Arendal is located near the middle of the *c.* 200 km long stretch of the Norwegian coastline named 'Sørlandet' (roughly the coastline between the Oslo fjord and the southern tip of Norway, see fig. 3.2.2). The bedrock along this coast consists mainly of acidic, crystalline rocks resistant to erosion, belonging to the proterozoic Bamble Complex (fig. 3.2.1; Padget 1988). The large-scale relief is characterised by a seaward-dipping peneplain which probably owes its formation to deep weathering during the Mesozoic. Repeated glaciations during the Quaternary (last 2.7 million years) have eroded zones of weak crystalline bedrock, and carved numerous smaller fjords into the coastline, but much of the intervening landscape exhibits fewer signs of glacial erosion. The outermost coastline is characterised by a distinctive landscape (in geomorphology referred to as 'skjaergaard'), with innumerable glacially sculpted islands and small skerries that are separated by deep and narrow sounds and channels.

Deglaciation and shoreline history

Norway was completely covered by the Scandinavian Ice Sheet during the Last Glacial Maximum *c.* 20,000 cal years ago (note that calendar years, abbreviated 'cal years (BP, *before present*)', are used throughout this chapter). The ice sheet expanded far south on the continent and also across the North Sea to the British Isles. The submarine Norwegian Channel is more than 700 m deep and follows the coastline from the Oslo fjord all the way around the southern tip of Norway. During the last glaciation, this channel was occupied by a fast-flowing ice stream that, much like a large river, evacuated ice from southern Norway and Sweden. The ice stream was grounded well below sea level and was the first part of the ice sheet to respond to deglaciation (Svendsen *et al.* 2015). Rising global temperature and rising eustatic sea level following the last glacial maximum caused the Norwegian Channel Ice Stream to retreat by 20,000–17,000 years ago.

Rapid shrinkage of the Scandinavian Ice Sheet was temporarily halted during the cold chronozone termed the Younger Dryas (12,700–11,500 cal years ago, *cf.* Lohne *et al.* 2014). The ice margin re-advanced several tens of kilometres along the western coast of Norway (Mangerud *et al.* 2016), producing many prominent ice-contact deposits such as end moraines and large deltas. End moraines suggesting glacial advance are also found along the Sørlandet coast, where they are correlated to the famous Ra moraine in the Oslo fjord region (fig. 3.2.2; Andersen 1960; Hughes *et al.* 2015). However, there are limited data that document the extent and timing of the advance along this coastline (Andersen 1960; Bergstrøm 1995; Bergstrøm 1999; Bergstrøm & Jansen 2001). The age of the Ra moraine given in existing literature is 12,600 years, placing it within the earliest part of the Younger Dryas (fig. 3.2.2; Sørensen 1979; Bergstrøm 1995; Hughes *et al.* 2015). Based on new results from this study, we find that the ice sheet retreated from the Ra position 500–1000 years later than previously suggested (see under "Discussion").

The history of shoreline displacement in the study area is typical for a formerly glaciated coastline. Marine limit, which marks the highest postglacial shoreline level, is found from around 65 m.a.s.l. near Arendal to *c.* 80 m.a.s.l. near Tvedestrand (fig. 3.2.12). The marine limit shoreline dates to the period immediately after regional deglaciation, and is in some places along the Sørlandet coast marked by raised delta terraces. The deltas were built by glaciofluvial material deposited into the sea by large glacial rivers during recession of the glacier margin.

The marine limit elevation along Sørlandet rises towards the northeast, with a gradient of about 1 m/km. The limited amount and geographic spread of observational data makes compiling shoreline isobases a difficult task, but based on available data and correlation to the Swedish west coast, Sørensen *et al.* (1987) suggested a postglacial (*c.* 7400 cal years BP) isobase orientation of 335°, i.e. near perpendicular to the coastline at Sørlandet. The uplift pattern reflects the variation in ice sheet thickness at the peak of the last glaciation.

The shoreline has fallen (regressed) from the marine limit until today, but the regression has occurred at a highly variable rate. A sea level rise (transgression) of many meters has been mapped along the entire outer western coast of Norway and dated to the 'Tapes' period (*c.* 9000–7000 cal years ago). The Tapes transgression is also well documented farthest south at Lista (fig. 3.2.2; Romundset *et al.* 2015), but did not take place

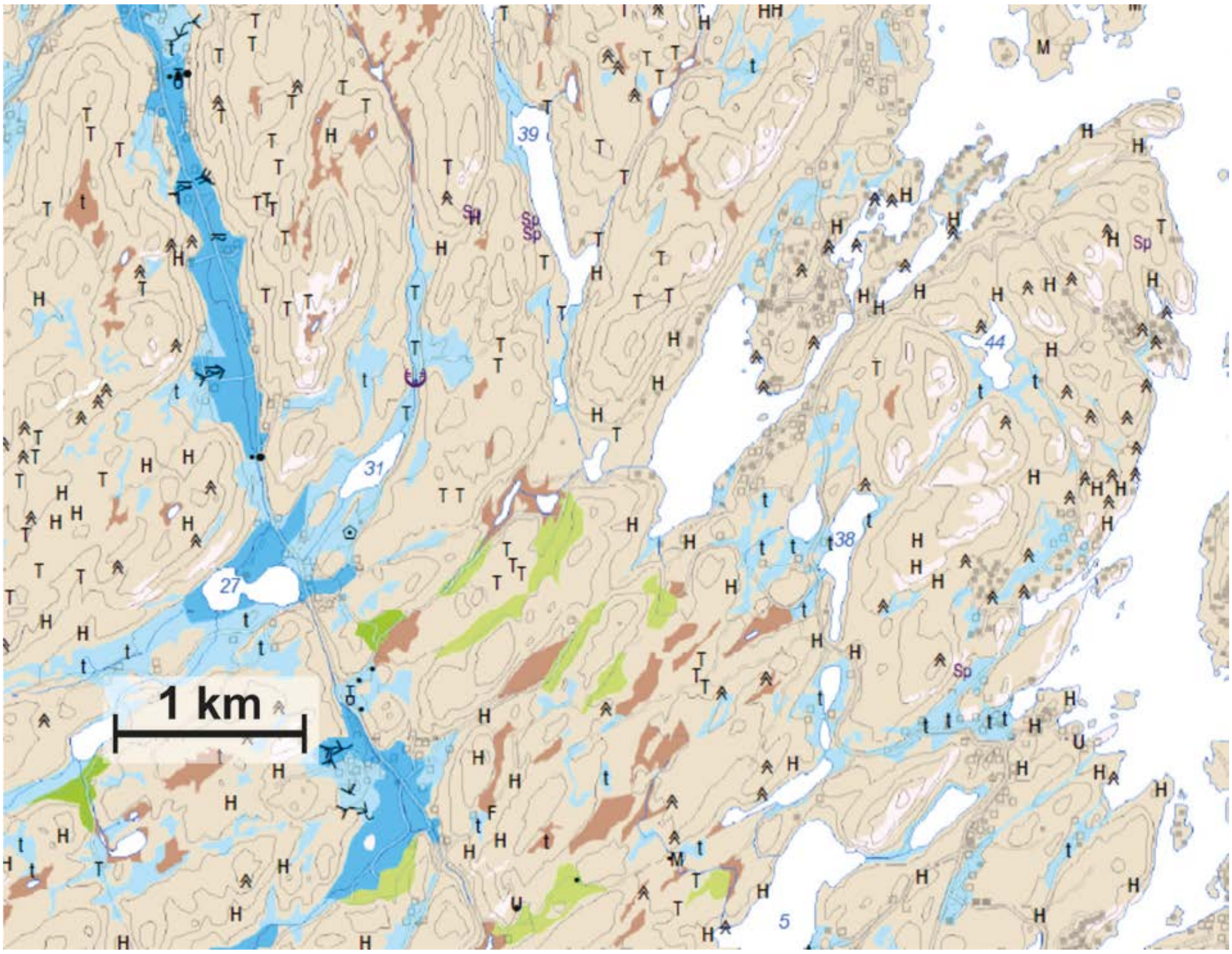

Figure 3.2.3: Part of a preliminary 1:50,000 scale geological map of surficial deposits and landforms (Romundset and Lakeman *in prep*.), showing the areas around Kvastad and Tvedestrandsfjorden. Bedrock with a thin cover of soil and vegetation (light brown colour) dominates on this coastline. A mostly thin cover of fine-grained marine sediments (blue) is frequently found in valleys and depressions below the marine limit. Patches of till left by the ice sheet (green) is found in some places inland.

where magnitudes of the glacial rebound were higher due to a larger former ice load, e.g. in the Vestfold area (fig. 3.2.2; Sørensen *et al*. 2014a). How far northeast from Lista along Sørlandet the transgression reached, was unknown prior to this investigation. Sørensen *et al*. (1987) suggested that relative sea level in the Arendal-Tvedestrand area during the Tapes period was near or slightly above 20 m.a.s.l.

Mapping of the surficial deposits in this region indicates that marine sediments are common in many valleys and topographic depressions below marine limit (fig. 3.2.3; Riiber & Bergstrøm 1990; Bergstrøm & Jansen 2001; Romundset & Lakeman *in prep*.). The deposits are dominated by clayey, often calcareous silt, with winnowed and littoral sand and gravel being common near the surface. The deposits represent the former sea-floor or littoral zone and constitute fertile and valuable areas for agriculture.

Sea level change – processes and concept

Sea level change is governed by a number of different processes (summarised in fig. 3.2.4). These can be separated into three groups: eustatic, isostatic and thermosteric changes. *Eustasy* describes the balance between water stored in ice sheets and in oceans, and during the Last Glacial Maximum caused on average 125 m lowering of sea level globally. The sea level was locally variable, however, during the last glaciation, partly because the distribution of water in the oceans is affected by geoidal gravity, i.e. from large landmasses and ice sheets. *Isostasy* is the term used for vertical uplift and depression of the Earth's crust and is the dominant mechanism underlying past relative sea level changes along formerly glaciated coastlines. *Thermosteric changes* in sea level are caused by varying salinity and temperatures of ocean water.

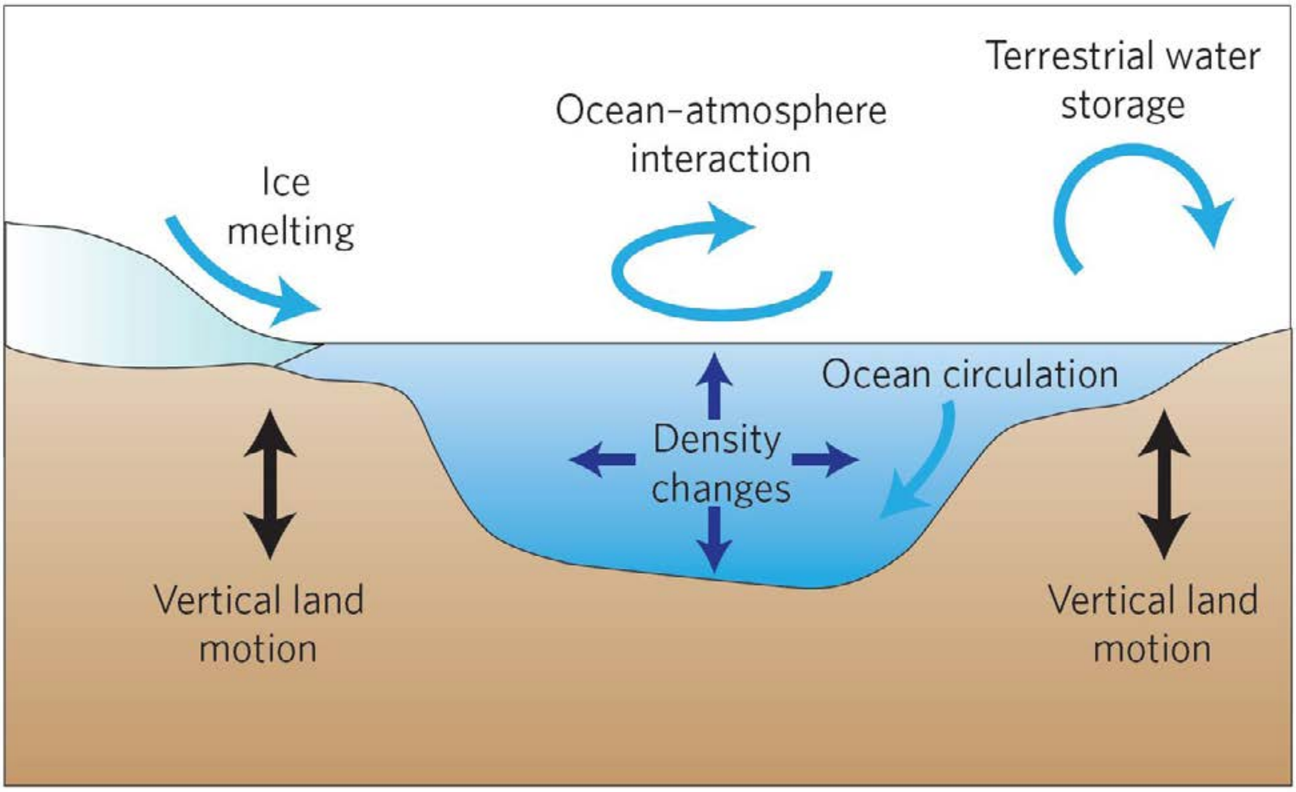

Figure 3.2.4: Processes that influence changes in relative sea level (Milne *et al.* 2009).

The concept of 'shoreline displacement' or 'relative sea level change' in geology refers to sea level change locally at a coastline, where changes both in sea level and land level contribute to the resulting fall (regression) or rise (transgression) of a shoreline position. The typical postglacial development along the Norwegian coastline is a net regression, where eustatic sea level rise has compensated for a significant share of the total glacio-isostatic rebound (fig. 3.2.5).

METHODS

Isolation basins

In this study we make use of isolation basins (fig. 3.2.6; e.g. Hafsten 1960; Kjemperud 1981) to reconstruct the history of relative sea level change. Isolation basins are natural topographic depressions that at different times are either connected to or isolated from the sea by changes in relative sea level. They provide detailed geological archives of past sea level change, given that the following requirements are fulfilled: (1) basins are not dammed by deposits or peat, but have outlet thresholds of solid bedrock that can be levelled to a precise elevation representing the relative sea level (mean high tide) during isolation, (2) basins are in a sheltered position from the sea and deep enough to contain undisturbed records, (3) basins are relatively small so that sedimentation rates were sufficient to deposit a high-resolution record, and (4) there are a number of closely spaced basins available at variable elevations below the marine limit. The last point is important when wanting to reconstruct relative sea changes over time. Large distances between basins

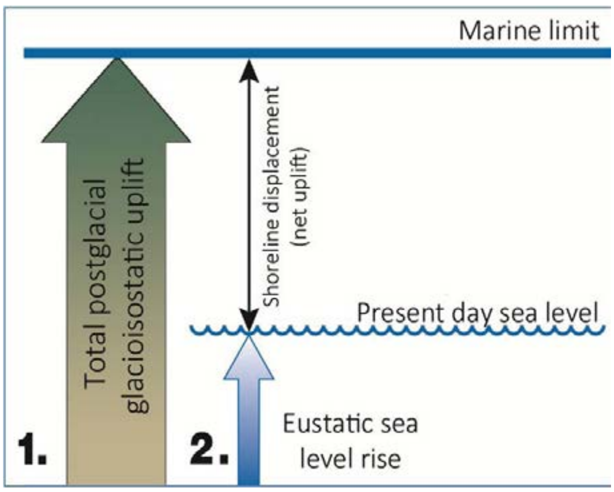

Figure 3.2.5: A schematic illustration showing how the change in shoreline elevation is the combined result of eustatic sea level change and glacioisostatic uplift (modified from Sveian 1995).

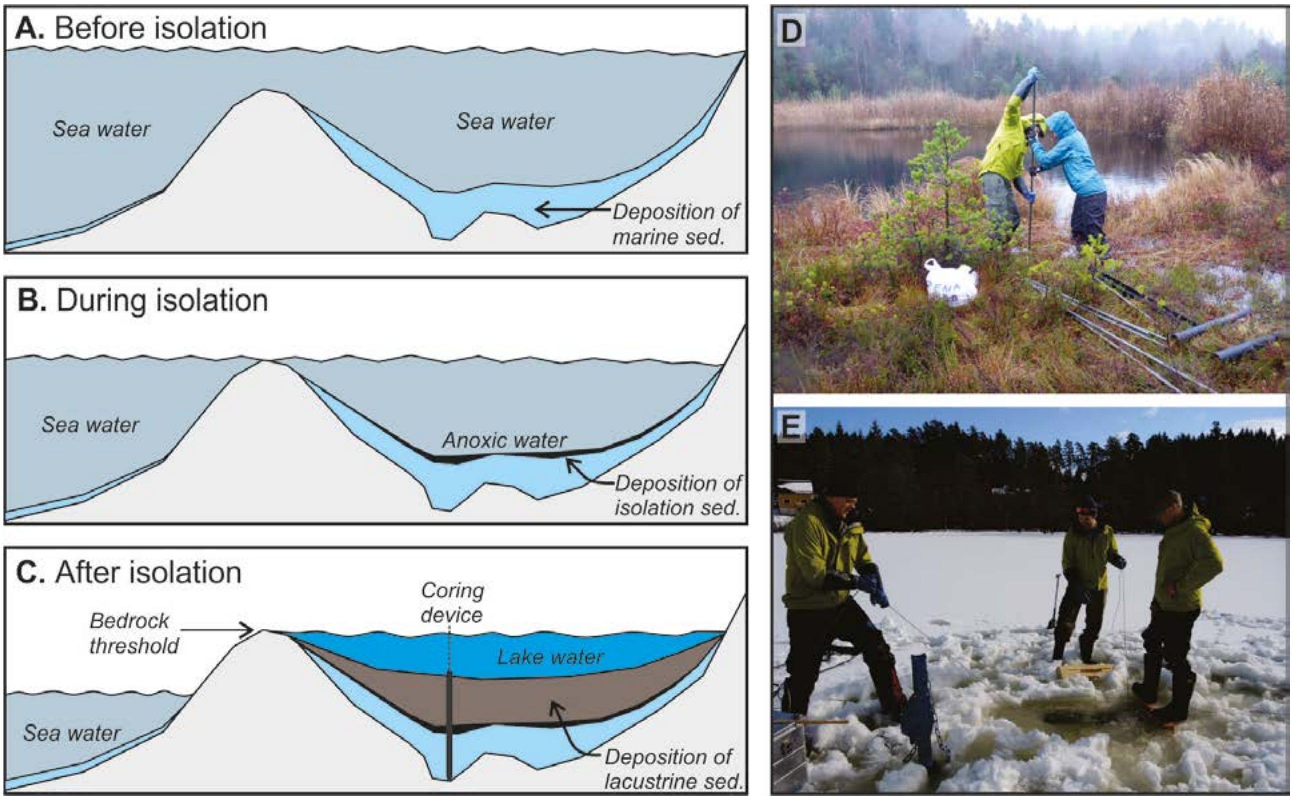

Figure 3.2.6: Principle of the isolation basin method, modified from Kjemperud (1981). A: A cross-section of the coastline with relative sea level well above a bedrock depression. Marine sediments (silt and organic debris) are deposited.
B: The elevation of the bedrock threshold is now above mean sea level but still below high tide and some salt water is still exchanged across the threshold. The basin water is depleted of oxygen and few organisms can survive. Deposition of the isolation boundary takes place (often black and densely laminated organic sediment). C: The basin is isolated (above high tide) and lacustrine gyttja is deposited. D: Coring with a "Russian type" peat corer from a floating bog surface.
E: Coring with a piston corer on a frozen lake.

lead to higher uncertainties because uplift rates have varied over short distances and, thus, need to be corrected for.

Sediment sequences are collected from the basin deposits using various types of coring equipment. In this study we have used two corers: a traditional peat corer (Jowsey 1966) and a wire-controlled piston corer (Nesje 1992). The peat corer can be used from bog surfaces and at shallow lakes (< 5 m deep) to recover half-cylinder samples of various diameters (5, 7 or 11 cm) and up to 1 m length. The piston corer can be used in deeper lakes to collect cylindrical samples of 11 cm diameter. Core lengths are restricted by the length of the tube, usually 6 m. Solid lake ice is a great advantage during field work because it provides a stable platform for coring operations.

Coring one basin (including coring at several sites to map lateral variations in lithology) typically takes one day for three persons, if nothing unexpected occurs. The cores are photographed, described, labelled and sealed in the field before transportation to the laboratory. Samples need to be kept in a cold storage prior to, and in between, analyses, to prevent degradation of organic material.

Levelling of basin thresholds (the elevation at the outlet) is a crucial part of the work. This can be done in different ways, but measuring with a differential GPS is simple and accurate where applicable (it needs satellite connection through cell phone network). Thresholds need careful examination and often probing with a 1 m long stainless steel soil sampler in order to confirm the lowermost passpoint over bedrock, since peat and fluvial gravel often cover the areas. The catchment of each basin also needs to be surveyed in case there is risk of disturbance of the basin environment by slides, rock falls or re-deposition from unconsolidated deposits.

Determining precise isolation boundaries using macrofossil analyses

Macrofossils are remains of animals and plants that are (barely) visible to the naked eye, e.g. seeds, shells and insect parts. Most of such material is rapidly decomposed in nature, but if transported into a lake macrofossils may be well preserved in the lake floor

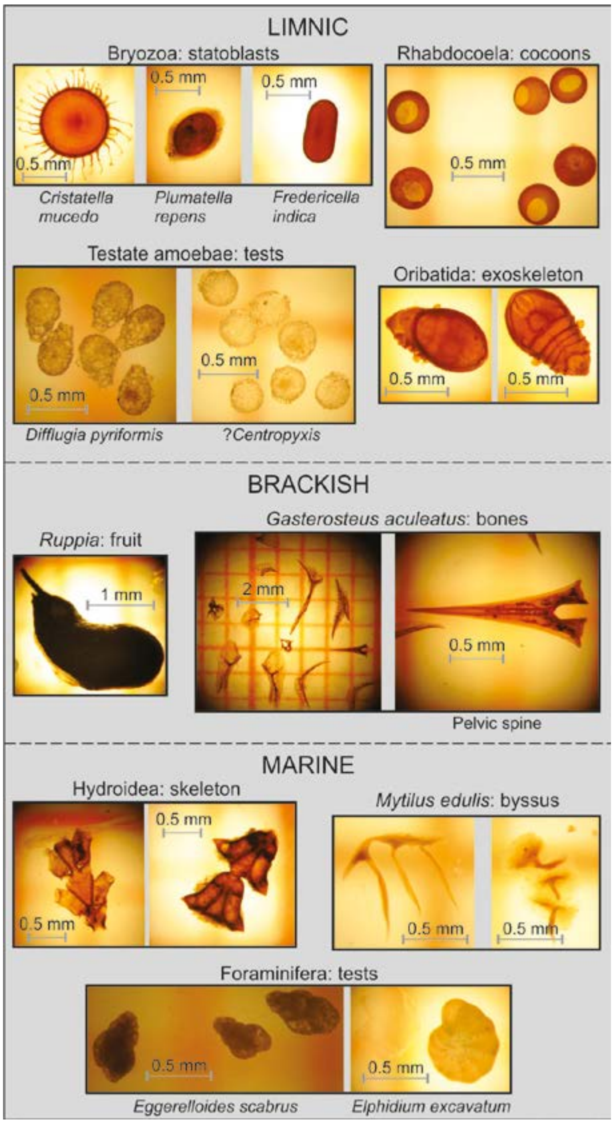

Figure 3.2.7: Examples of animal and plant macrofossils that are useful in isolation basin analysis (Romundset *et al.* 2011).

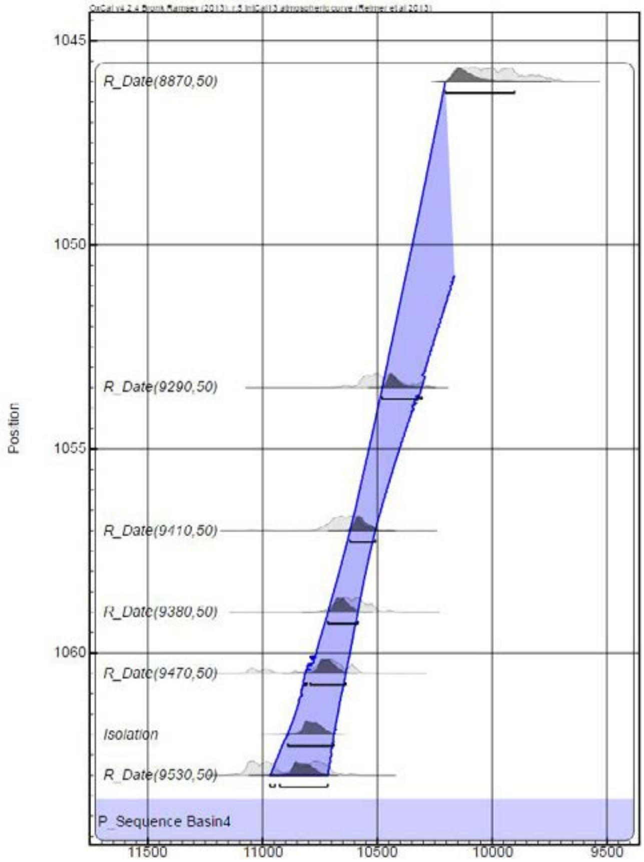

Figure 3.2.8: An age-depth plot of ages from six samples that were radiocarbon dated from Basin 4 in this study. The plot shows the probability and 2 σ distribution of each date in calibrated years along the x-axis and the stratigraphical depth in centimetres along the y-axis. The dates were modelled using the P_Sequence function in OxCal (Bronk Ramsey 2008; Bronk Ramsey 2009), which narrows the confidence interval of each date and further constrains the age of the isolation boundary.

sediments. Many of the remains come from organisms that are unique to marine or limnic environments and are therefore useful for analysis of the isolation boundary in a lake record (Bennike *et al.* 2002; Romundset *et al.* 2011). In this study, sediment samples cut from different levels of the cores were wet-sieved at 125 µm mesh width and the remains studied under a stereomicroscope. The changes in biostratigraphy give a detailed account of the isolation history of a basin, and the exact isolation boundary – the sediments that represent the last incursion of marine water into the basin during high tide - can in most cases be determined within ± 1 cm depth. This means that in this study, the uncertainty inherent in radiocarbon dating and calibration is greater than that associated with assigning the isolation boundary on the basis of the examined biostratigraphy, given the overall high sedimentation rates that can be deduced from the long records.

Radiocarbon dating and age modelling of the isolation events

All radiocarbon dates used for the sea level reconstruction have been obtained from identified remains of terrestrial plant macrofossils (not bulk samples), and dated using accelerator mass spectrometry (AMS). The ages have been calibrated with the computer software OxCal v4.2 (Bronk Ramsey 2001) using the Intcal13 dataset (Reimer *et al.* 2013) and all calibrated ages are given as time intervals (with 2 σ error), in years before present (AD 1950). Radiocarbon ages of marine samples were calibrated using the Marine13 dataset

(Reimer *et al.* 2013) with a regional ΔR-value of -3 ± 22 years (Mangerud *et al.* 2006), representing coastal waters along this part of the Norwegian coastline. Ages of the isolation events are substantiated by dating a series of samples from across each isolation boundary, often with additional dates at levels somewhat above and below. Where applicable, the series of dates were subjected to Bayesian probability analysis using the P_Sequence deposition model (Bronk Ramsey 2008; Bronk Ramsey 2009), which is included in the OxCal software (fig. 3.2.8).

Dates of marine shells from basal sediments

An important part of reconstructing relative sea level changes at a locality is to determine not only the elevation but also the age of the marine limit – the oldest shoreline from where the relative sea level curve starts. The age of the marine limit equals the timing of local deglaciation, i.e. when the ice sheet retreated inland from the modern coastline.

Deep isolation basins are archives of such information, since the first deposition of sediments will be recorded at the bottom of recently ice-free topographic depressions. Some species of cold-water molluscs tolerate cold and turbid glaciomarine conditions well; they spread rapidly in waters near an ice sheet and are common in deglacial deposits from such environments. In this study we cored as deep as we could in seven selected basins, until our coring equipment hit bedrock or diamicton/till. We picked shells from the lowermost few decimetres of up to 7–8 m long glaciomarine units. The ages of these shells provide minimum-limiting constraints for when the study area became ice free.

BASINS AND RESULTS

The following section presents the investigated basins (ranged from the highest elevation and downwards), their threshold elevations and deposits, including

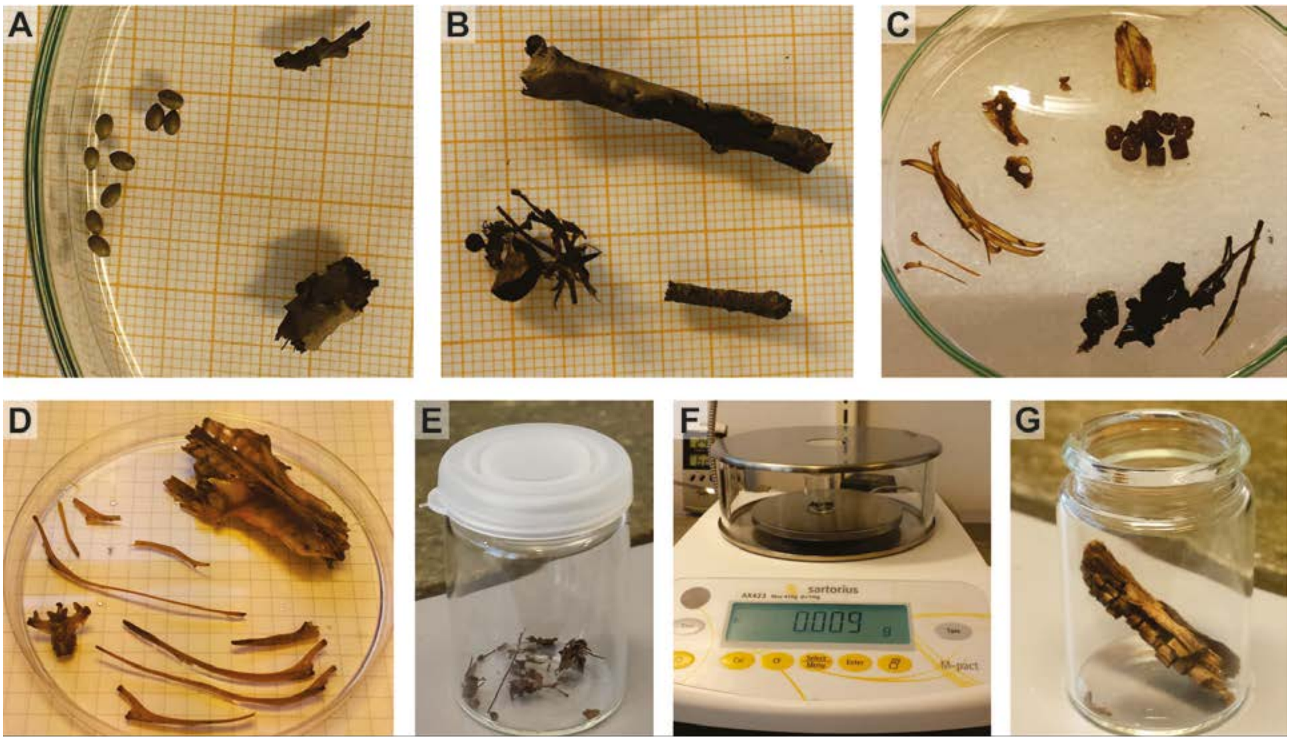

Figure 3.2.9: Some images of hand-picked and cleaned terrestrial plant macrofossils that were radiocarbon dated. A: Nine seeds from a rush plant (Juncus), weighing 6 mg; a small willow (Salix) twig with buds, weighing 10 mg and a larger birch (Betula) twig with attached cortex, weighing 25 mg. These were all found at the isolation boundary in Basin 16 and dated separately; all three yielded identical ages. B: Three other representative dating samples. C: Various remains of a marine fish and some terrestrial leaves and a pine needle (lower right). D: Bones of a long-tailed duck (Clangula hyemalis), a rare finding from 11 m depth in the sequence from Basin 4: the pelvis, several ribs and a vertebra. Dated to c. 11 ka. E: A sample of selected plant macrofossils packed in a sterilized vial. F: The same sample being weighed before being submitted to the radiocarbon lab (9 mg – a typical sample size). G: A larger piece of wood ready for dating. Such larger fragments may in theory have remained on the ground for some time after death, prior to deposition in the lake, and may thus pre-date their stratigraphical depth. However, dating of many parallel samples of larger and smaller fragments, both in this and other studies, shows that this is not a significant issue.

the determined ages of the isolation events. Basin numbers, official names and geographical position are given. The two basins at Bjørnebu are presented last. Some basins lack names or have identical names, these are given informal names or name additions in brackets. Figure 3.2.10 provides an overview map of the geographical distribution of the basins. For even further details, see Romundset *et al*. (2018).

Basin 1 – Butjenna, 88.9 m.a.s.l. (58.6003°N 8.8882°E)
Butjenna consists of two small, narrow lakes surrounded by peat that occupy the upper reaches of a small valley just south of the local watershed boundary between Fiane and Kvastad, *c*. 650 m upstream from Basin 2. A stream crosses the bedrock threshold towards the south. We cored at many sites in the basin and identified the longest sedimentary record (about 11 meters) in the area between the two lakes. Sedimentological and biostratigraphical analyses indicate that the entire record is lacustrine, including the lowermost gyttja and underlying greyish silt found in the bottom few centimetres. We sampled two tiny twigs from the base of the core, which were dated to 11,610–11,220 cal years BP. The absence of marine sediments in the lake indicates that the basin is located above local marine limit.

Basin 24: Eikåstjenna 85.7 m.a.s.l., tilt adjusted to 80 m.a.s.l. (58.6241°N 9.0047°E)
The Eikåstjenna basin measures *c*. 300 x 100 m and has a well-defined bedrock sill that we identified 64 cm below the water surface of the lake. The elevation of the threshold was determined using a LiDAR elevation model (as no dGPS connection was available when investigating the threshold depth). However, Eikåstjenna is located approximately six km northeast of the other high-elevation isolation basins (nos. 2, 3 and 4) and thus on a slightly higher isobase (fig. 3.2.10). The relatively large distance as well as the steep isobase gradient immediately following deglaciation mean that Basin 24 needs to be corrected for differential uplift in order to be presented as part of the same relative sea level curve. Using a shoreline tilt of 1 m/km, based on elevations of raised deglacial glaciofluvial deltas along Sørlandet (Try 1951; Andersen 1960; Thorsen 1965), we adjust the elevation of Eikåstjenna to 80 m.a.s.l.

The record of the basin is more than 14 metres long and consists almost solely of lacustrine gyttja with fine-grained organic detritus. Marine sediments were identified only at the base of the core, where an isolation boundary was determined at 1393 cm depth and dated to 11,770–11,260 cal years BP. An additional radiocarbon age 10 cm above this stratigraphic level confirms the isolation age.

Basin 2: Kroktjenna "høge" 78.6 m.a.s.l. (58.5945°N 8.8938°E)
The outlet stream of this *c*. 100 x 100 m large basin drains to the south across a visible bedrock sill. The isolation boundary was located at 1088 cm depth. The age was estimated by extrapolating (assuming a steady sedimentation rate) from three radiocarbon ages obtained from 5–9 cm above the isolation contact. This method indicates that the isolation occurred *c*. 11,350 ± 200 cal years BP.

Basin 3: Midttjenna "høge" 68.2 m.a.s.l. (58.5959°N 8.9219°E)
This 80 x 140 m large basin also has an outlet across visible bedrock. We analysed and dated the isolation sequence from two different core sites using seven radiocarbon dates. This yielded identical ages for the isolation event, 11,090–10,600 cal years BP.

Basin 4: "Johan Olsson-myra" 63.2 m.a.s.l. (58.5808°N 8.9438°E)
This small basin measures 50 x 100 m and is completely in-filled by a peat bog. The visible bedrock threshold is subaerial, submerged only during periods of heavy rain. The isolation boundary is well-defined at 1062 cm depth and its age, 10,890–10,690 cal years BP, is based on Bayesian modelling of six radiocarbon dates across the boundary. An additional and rare finding from this basin was the skeleton (ribs and pelvis) of the marine bird *Clangula hyemalis* (long-tailed duck, Norw.: *havelle*) which was recovered from the core immediately below the isolation boundary. The bones were directly dated to 11,060–10,680 cal years BP. Five samples of mollusc shells were also collected from the lowermost sediment in the core and dated, yielding minimum-limiting ages for local ice sheet retreat.

Basin 5: Rosstjenna 59.0 m.a.s.l., tilt adjusted to 64 m.a.s.l. (58.5542°N 8.8699°E)
The isolation boundary in this small basin (50 x 100 m) was located at 773 cm depth and was dated to 11,000–10,790 cal years BP. The basin threshold is covered by peat but was measured using a soil sampling probe. The elevation of the basin was adjusted in order to be representative for Hanto, which is located 5 km to the east (fig. 3.2.10). Comparison with the isolation basins at Bjørnebu gives a shoreline tilt for this point in time of ca. 1 m/km (see *Discussion* below), which provides an adjusted elevation of 64 m.a.s.l.

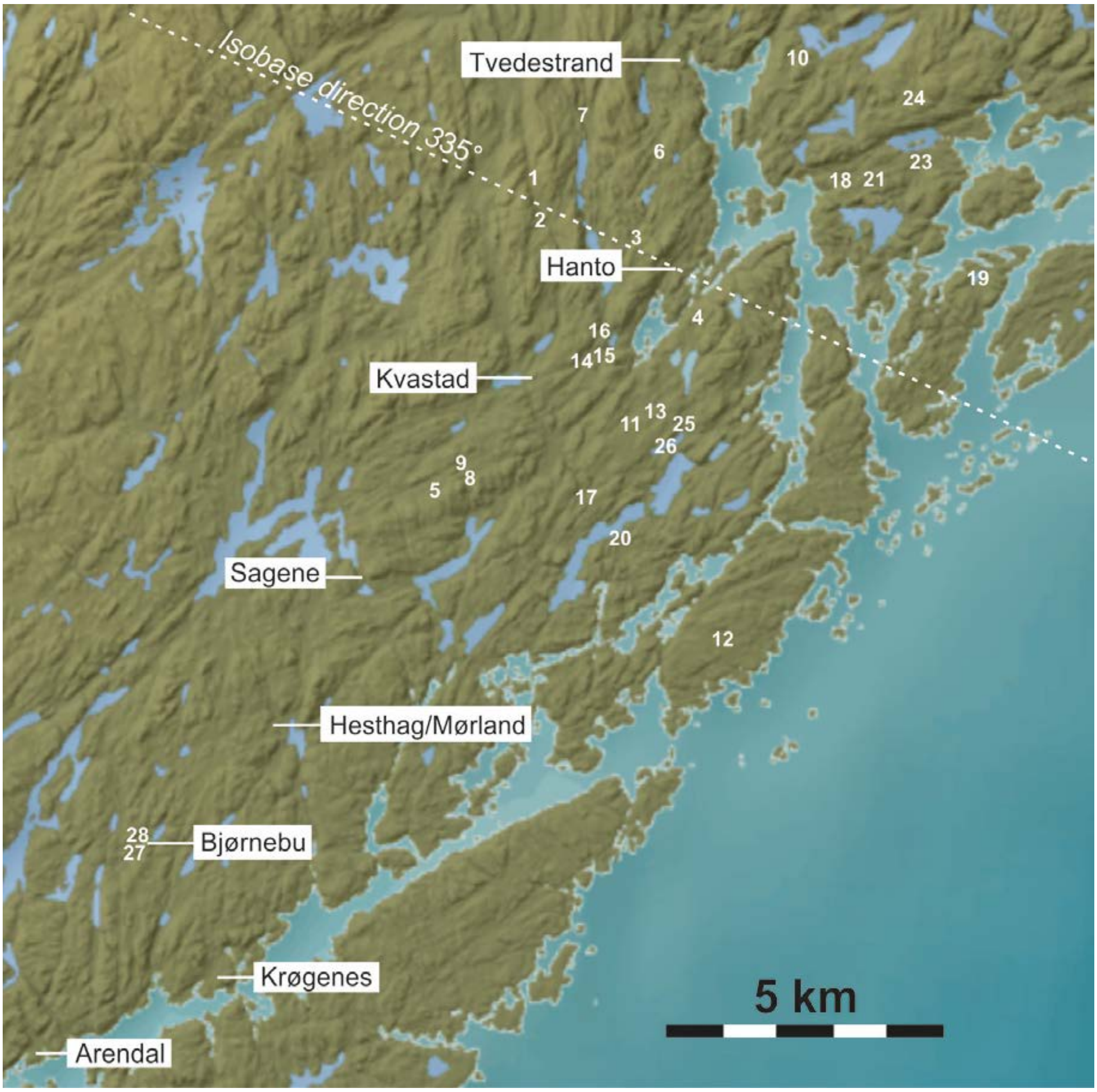

Figure 3.2.10: Overview of the study area between the towns of Arendal and Tvedestrand. Main archaeological excavation sites are marked, as well as the localities Hanto and Bjørnebu, from where we reconstruct the relative sea level history (Fig. 3.2.12). The numbers show the geographical position of each investigated basin. See text for details including coordinates for each core site. Modified from www.norgeskart.no.

Basin 6: Gladstadtjenna 52.8 m.a.s.l. (58.6092°N 8.9254°E)

Five radiocarbon ages from two sediment cores in this narrow basin (40 x 150 m) constrain the age of the isolation boundary to 11,150–10,740 cal years BP. One additional radiocarbon age that was anomalously young was omitted. The bedrock sill was located below half a metre of sand and gravel in the outlet stream.

Basin 7: Øygardstjenna 52.0 m.a.s.l. (58.6110°N 8.9023°E)

Two separate basins are found in this small valley. The southern basin, measuring approximately 130 x 40 m, was sampled. The outlet stream crosses visible bedrock towards the south. The isolation boundary was found at 1014 cm depth and its age was determined to be 10,770–10,420 cal years BP using three radiocarbon dates.

Basin 8: Kroktjenna "øvre" 46.9 m.a.s.l. (58.5579°N 8.8783°E)

For this small basin (50 x 80 m) the bedrock threshold was not directly located, as it was obscured by compact diamicton. The elevation is therefore more uncertain than for the other basins and it could in theory have been higher in the past. However, there is no evidence of significant erosion and incision of the basin outlet following isolation from the sea. The age of the isolation contact is 10,580–10,250 cal years BP and is based on five radiocarbon dates from two different cores. This age is in accordance with the neighbouring Basin 9, which is only *c.* 1 m lower. Three samples of marine mollusc shells from the lowermost silt in one of the cores (nearly 4 m below the isolation boundary) yielded minimum-limiting ages for local deglaciation.

Basin 9: Kroktjenna "nedre" 46.7 m.a.s.l. (58.5568°N 8.8758°E)

The inner part of this basin is occupied by a lake (100 x 200 m) but we cored from floating peat nearer the outlet. The bedrock threshold has been somewhat modified by humans to improve drainage, but we identified the original outlet bedrock surface next to the stream. We measured the isolation boundary at 590 cm depth and four radiocarbon ages provide an isolation age of 10,520–10,240 cal years BP.

Basin 10: Tranbærlona 46.0 m.a.s.l. (58.6251°N 8.9628°E)

This is a small (60 x 140 m) sub-basin in the SW end of a much larger lake, Østeråvannet. Thus, the sea level record of Tranbærlona is governed by the threshold at the outlet Østeråvannet. There is a small concrete dam at this outlet, probably built to secure controlled drainage of the outlet stream. However, we levelled the elevation of bedrock next to the dam and did not see any indication of human altering of the natural sill. The isolation boundary was identified at 718 cm depth and dated to 10,650–10,280 cal years BP.

Basin 11: Eikelandsmyra 40.5 m.a.s.l. (58.5686°N 8.9259°E)

The basin is found in a large area (150 x 600 m) of bogs and ponds. The threshold is covered by peat, but we detected and levelled bedrock near the main outlet. We cored many sites in this area to map the depth and condition of the deposits and collected a core from near the northern margin of the basin, about 100 m from the outlet. Analyses document a transition from marine to lacustrine sediments at 666 cm depth but with sedimentological evidence of erosion during the isolation phase, indicating a hiatus in the record. Five samples were dated but these provide only maximum- and minimum-limiting ages (10,910–9610 cal years BP) for the isolation event, which is thus relatively poorly constrained.

Basin 12: Kringlemyra 37.6 m.a.s.l. (58.5359°N 8.9582°E)

In contrast to all other basins in this study, this small basin (30 x 80 m) has a poorly defined threshold and an exposed location towards the open ocean. It is thus not a well-suited isolation basin, which is also reflected in the sedimentary record. There is a transition from marine to lacustrine sediments at 276 cm depth, but with indications of disturbance of the lake floor during isolation, probably due to the shallow depth as well as the exposed location. The determined isolation age of 10,220–9920 cal years BP is therefore given less weight in the relative sea level reconstruction.

Basin 13: "Marit Bjørgen-myra" 36.2 m.a.s.l. (58.5690°N 8.9325°E)

This *c.* 50 x 100 m basin has a very limited drainage area. The bedrock threshold is subaerial, with only periodical outflow from the basin. We cored several sites along a longitudinal profile and found the deepest areas in the central basin. Here, a core was recovered that included a well-defined and laminated isolation boundary at 788 cm depth. The boundary was dated to 10,270–9940 cal years BP using three radiocarbon dates.

Basin 21: Eidbomyra 31.7 m.a.s.l. (58.6052°N 8.9917°E)

The central part of this *c.* 70 x 130 m basin was cored. The bedrock threshold is visible where a stream flows towards the north. Four radiocarbon ages straddling the isolation boundary at 756 cm depth gave congruent ages and indicate that the isolation took place 9910–9550 cal years BP. The relatively large age span despite a series of four radiocarbon ages is due to larger uncertainties in the calibration procedure for this period (i.e. a less-steep calibration curve). The age is most likely towards the younger part of the given interval, based on the resulting probability distribution of the modelled age. Four additional samples of marine mollusc shells from the base of the sequence, at nearly 12 metres depth, give a minimum-limiting age local deglaciation.

Basin 14: Alfstjenna 28.0 m.a.s.l. (58.5749°N 8.9102°E)

This is another long and narrow basin (*c.* 300 x 50 m) that was cored along a longitudinal profile and finally

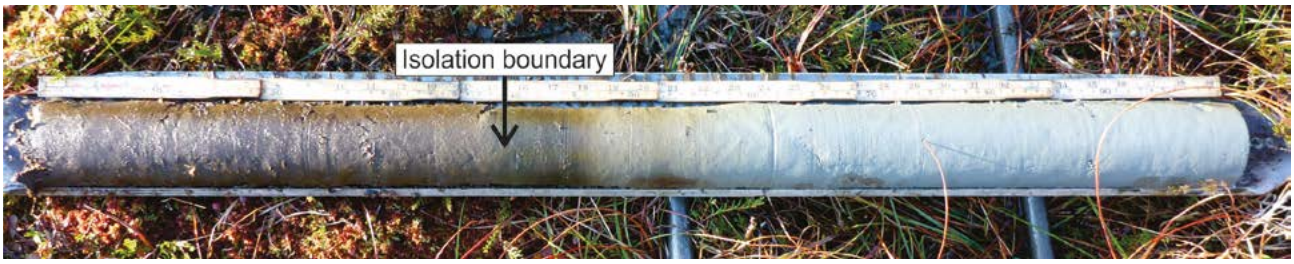

Figure 3.2.11: A one meter long core sample from 4.5–5.5 m below the surface of Alfstjenna, covering the isolation sequence. Right is down-core. Blue-grey marine silt is overlain by a *c.* 5 cm thick laminated brackish-water deposit, which is overlain by brown lacustrine gyttja. The exact level of the isolation boundary (i.e. last input of marine water to the basin) occurs at the upper contact of the laminated brackish deposit (i.e. to the left of the centre of the picture).

sampled near the outlet to the north (fig. 3.2.11). Thick peat occurs in the threshold area, but the bedrock elevation was confirmed at the outlet stream. The isolation boundary was found at 486 cm depth and was dated to 9530–9310 cal years BP based on five samples.

Basin 15: Midttjenna "låge" 27.5 m.a.s.l. (58.5745°N 8.9127°E)
This basin lies adjacent to and only slightly below Alfstjenna. Peat covers the threshold area but we found bedrock by probing next to the outlet stream. An incomplete depositional sequence was recovered. A transition from marine to lacustrine sediments was identified at 471 cm depth but sedimentological evidence indicates that a hiatus occurs close to the isolation contact. The available radiocarbon ages, therefore, only provide maximum- and minimum-limiting ages (9500–8920 cal years BP) for the isolation event.

Basin 25: Østre Kroktjenna 24.4 m.a.s.l. (58.5671°N 8.9405°E)
This is a 250 x 120 m large lake that was cored from ice in winter using a piston corer. We also surveyed the area in summer and found blocky till covering the outlet of the basin. The isolation boundary is well-defined at 594 cm depth, and was dated using six samples from above and below the boundary. Bayesian modelling of the sequence of dates yielded a well-constrained age of 7530–7460 cal years BP for the basin isolation. This basin is the highest in the study area for which isolation post-dates the Tapes period. Additionally, we dated three samples of terrestrial macrofossils picked from *c.* 3 metres below the isolation boundary. These date back to *c.* 9500 cal years BP (fig. 3.2.12), and the continuous marine sedimentation above this level documents that the shoreline did not fall below this elevation at the beginning of the Tapes period.

Basin 26: Vestre Kroktjenna 24.3 m.a.s.l. (58.5619°N 8.9375°E)
This lake is nearly 700 m long and about 100 m wide. The outlet stream crosses visible bedrock. It was cored from ice in the central part of the basin using a piston corer. The isolation boundary was identified at 1227 cm depth in the sediment core and dated to 7320–7170 cal years BP using four radiocarbon dates.

Basin 16: Revstjenna 21.6 m.a.s.l. (58.5799°N 8.9141°E)
This small basin (60 x 180 m) was also surveyed in summer but cored from ice in winter. The threshold is well-defined across sub-aerially exposed bedrock. Eight radiocarbon ages straddling the isolation boundary at 616 cm were obtained. They provide consistent results that were used to model the timing of isolation, 7200–7040 cal years BP.

Basin 17: Tjenna 18.5 m.a.s.l. (58.5533°N 8.9121°E)
Here, bedrock is visible at the threshold, and the isolation boundary was located at 396 cm depth in the small (150 x 70 m) basin. Four radiocarbon dates constrain the age of isolation to 6200–5980 cal years BP. Two additional dates of mollusc shell fragments constitute a minimum-limiting age (*c.* 11,500 cal years BP) for deglaciation of the area.

Basin 18: Eidbotjenna 11.5 m.a.s.l. (58.6060°N 8.9818°E)
This very small (30 x 60 m) basin was cored from ice. The threshold was surveyed in summer and bedrock was found at the outlet close to the neighbouring road. The basin contains a well-preserved sedimentary record of sea level change. The isolation boundary was identified at 465 cm depth and was dated to 4170–3960 cal years BP using a sequence of six radiocarbon ages straddling the isolation contact.

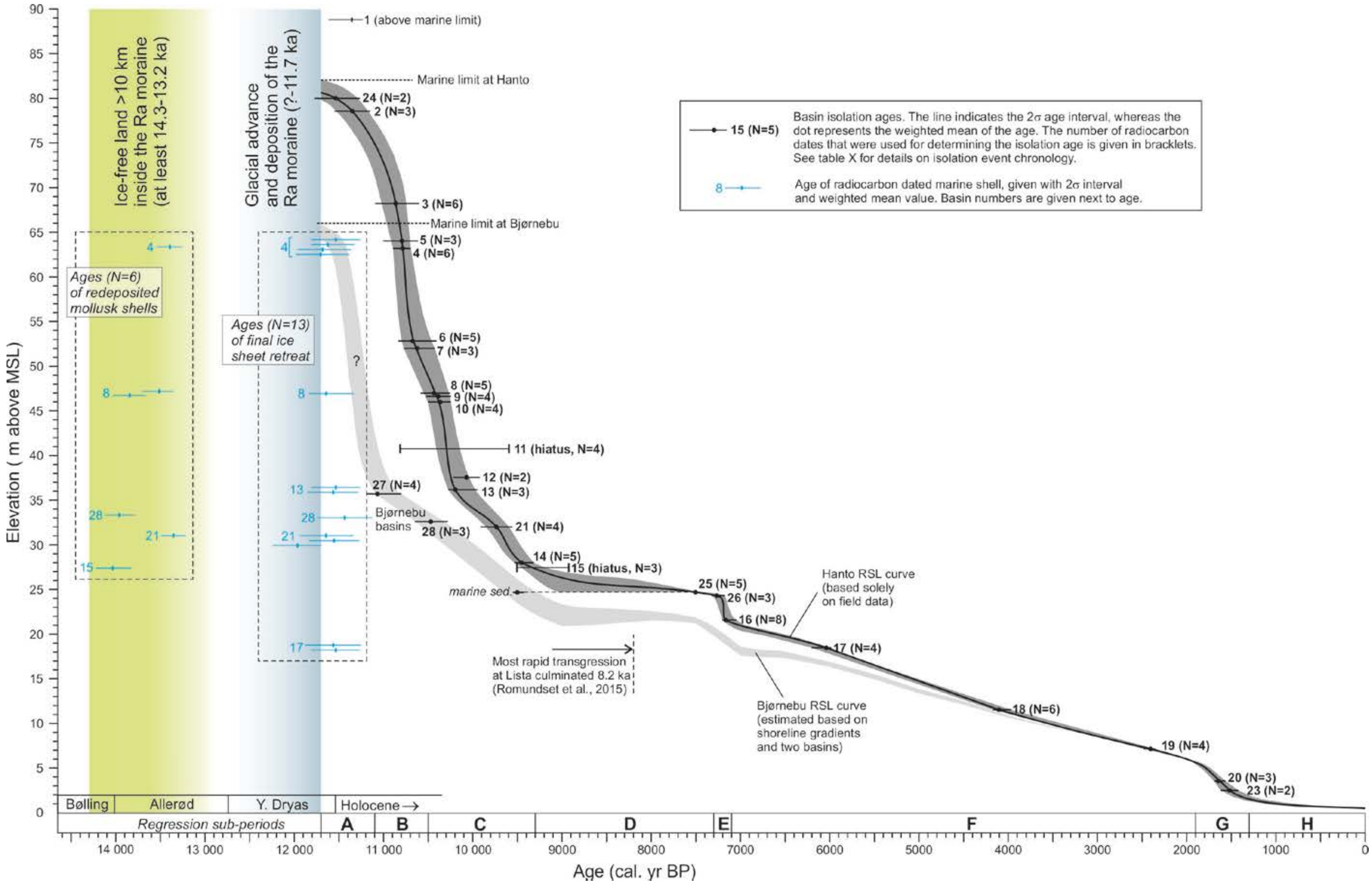

Figure 3.2.12: The new relative sea-level (RSL) reconstruction from this study. Dark grey curve represents the Tvedestrand area and light grey curve represents the Arendal area. See text for details.

Basin 19: Øygårdstjenna 7.2 m.a.s.l. (58.5913°N 9.0217°E)
This lake measures *c*. 320 x 80 m and was cored from ice. The outlet stream runs directly on bedrock. The isolation boundary was found at 362 cm depth and four dates document that the basin was disconnected from the sea 2480–2350 cal years ago.

Basin 20: Gullbergtjenna 3.6 m.a.s.l. (58.5470°N 8.9257°E)
This bog is about 350 x 100 m in size and lies adjacent to two larger lakes in the area. Thick peat covers the outlet area towards the larger lakes, but bedrock was found by probing and confirmed across the area. Several sites were cored in the field and two core samples for laboratory analysis were collected from the central basin and from near the threshold. The core from near the threshold contains the clearest isolation boundary, which was found at 310 cm depth and dated from three radiocarbon dates to 1690–1560 cal years BP.

Basin 23: Frydendal 2.3 m.a.s.l. (58.6097°N 9.0021°E)
The lowermost basin of this study is about 250 x 60 m in size, is occupied by a lake and dammed by a bedrock structure over which the outlet stream crosses. A core from near the middle of the basin was collected from ice in winter. The isolation boundary was identified at 220 cm depth. Due to difficulties in the laboratory of graphitizing the plant macrofossils, it was not possible to date the well-defined boundary directly. However, by assuming a linear sedimentation rate and extrapolating from two radiocarbon dates from 15–30 cm lower in the core, the isolation event is considered to have occurred 1620–1420 cal years BP.

Basin 27: Bjørnebutjenna 35.7 m.a.s.l. (58.4917°N 8.7845°E)
This basin comprises two sub-basins that measure about 100x100 m each and are connected by narrow but deep peat. There is visible bedrock at the threshold next to a field. A core from the central part of the inner sub-basin yielded a finely laminated and well-preserved isolation boundary at 697 cm depth. Based on four dates from immediately above and below this boundary it is concluded that the basin was isolated 11,250–10,860 cal years BP.

Basin 28: Enketjenna 32.6 m.a.s.l. (58.4936°N 8.7905°E)
This basin is 150 x 100 m large and was cored to bedrock at nearly 16 m depth. A relatively large stream runs across visible bedrock at the threshold. The basin is situated about 400 m from basin 27. The isolation boundary was identified at 730 cm depth and dated to 10,650–10,280 cal years BP using three radiocarbon ages. A sample of mollusc shells near the base of the sequence gives a minimum-limiting age (*c*. 11,600 cal years BP) for deglaciation of this area – which is similar to the timing of the onset of ice-free conditions at Tvedestrand.

DISCUSSION AND CONCLUSIONS

Deglaciation of Sørlandet – when did the ice sheet disappear?

In total 19 radiocarbon samples were dated from the lowermost basin deposits (plotted in fig. 3.2.12) and 13 of these yielded ages that overlap at 2 σ, clustering around 11,700–11,600 cal years BP – close to the Younger Dryas (YD) – Holocene boundary. The timing of deglaciation, 11,700 cal years BP, is the starting point for the relative sea level curve. The remaining six shell samples yielded ages spanning 14,000–13,000 cal years BP, i.e. from the Bølling-Allerød (B-A) interstadial, a nearly 2000-year warm period prior to the YD. These older dates are interpreted to record an ice-free coastal environment during the B-A, which was overridden by the ice sheet during the YD re-advance. The dated shells were possibly ice-transported and redeposited along with glaciomarine sediments into the isolation basins during ice marginal retreat from late-glacial maximum position attained during the YD. Thus, these older shells document an ice-free coastline during the B-A that extended at least 10 km inside the subsequent Ra ice margin.

The implications of these new results are: (1) that the Scandinavian Ice Sheet advanced > 10 km during the YD along this coastline, and (2) that the ice sheet margin remained at the Ra position until the end of the YD. Both of these conclusions constitute important new knowledge of the Quaternary geology, paleoclimate, and paleoenvironmental history of this part of Norway. The scale of the YD ice sheet advance is not wholly unexpected (cf. Bergstrøm 1995), but has hitherto not been documented in this part of Norway. The new age for the timing of ice sheet withdrawal from the Ra moraine is in conflict with regional reconstructions that impose an age of 12,600 cal years on the Ra ice margin (and ice sheet recession through the YD) from the Oslo fjord towards the southwest (Sørensen 1979; Bergstrøm 1995; Bergstrøm 1999; Mangerud *et al*. 2011; Hughes *et al*. 2015). Further research is needed to fully resolve the temporal variability of the Ra ice margin, and to ascertain the resulting paleoclimatic and paleoenvironmental implications for southern Norway.

The new relative sea level curve
Based on a new, comprehensive dataset, we present the main output from this work - a new relative sea level curve (fig. 3.2.12). The curve represents the area where the investigated basins are found, and can only be used for a limited region. Strictly, it represents the locality Hanto, because corrections for differences in the early Holocene HoHcrustal uplift rates are made for two basins (nos. 5 and 24) with reference to the isobase running through Hanto (fig. 3.2.10; Sørensen *et al.* 1987). Further corrections of basin elevations because of variable uplift rates are not needed for this study, due to the short distances between the basins.

It is important to note that the curve represents mean high tide sea level, meaning beach sediments and other raised shoreline deposits might be found several meters above the level shown on the curve, especially at exposed locations. The curve is depicted as a black line inside a dark grey zone. The grey zone represents the uncertainty envelope for the curve and should always be considered.

Estimated difference for the areas towards Arendal
The two sampled basins at Bjørnebu, about 4 km northeast of Arendal town (fig. 3.2.10), provide insight into how variable relative sea level changes have been across this area, especially for the earliest part of the Holocene. The two basin isolations are plotted in figure 3.2.12 and an estimated Holocene relative sea level curve for Bjørnebu is suggested (light grey). The shape of the curve is constrained by (1) the elevation and age of marine limit (Bergstrøm & Jansen 2001), (2) the age of isolation of the two Bjørnebu basins, and (3) the postglacial shoreline gradient, calculated by comparing the results of this study with relative sea level data from southern Vestfold (Sørensen *et al.* 2014a; Sørensen *et al.* 2014b).

For the different excavation sites between Arendal and Tvedestrand, the distance to the Hanto and Bjørnebu curves should be evaluated in order to estimate ages for levels at the specific sites.

Regression sub-periods (A–H)
The history of shoreline displacement at Hanto has been divided into eight time periods (A–H; fig. 3.2.12).

A: 11,700–11,100 cal years ago
The few hundred years following deglaciation were characterized by a significant but still relatively slow regression, with an average rate of 1 cm/year.

B: 11,100–10,500 cal years ago
This is the period of most rapid land emergence, as a response to the glacial unloading after the Younger Dryas. Regression rates were on average 4–5 cm/year, but most likely even higher for parts of this 600-year period.

C: 10,500–9300 cal years ago
The regression rate gradually decreased and through this period averaged about 2 cm/year. The new field data suggest variable rates through this period (on decadal-centennial timescales), but such variation cannot be fully resolved when taking the uncertainty into account.

D: 9300–7300 cal years ago
This is the period when the Tapes transgression took place along much of the western Norwegian coast. Along this particular coastline, indications of the transgression has previously been observed as far north as at Grimstad (Gabrielsen 1959). In the present study area, however, there was no transgression (at least not a significant one, i.e. larger than 1–2 m), but this was a long period when the shoreline position was almost unchanged due to minimal rates of glacioisostatic emergence.

E: 7300–7100 cal years ago
Three firmly dated isolation events document that there was a major drop in relative sea level occurring over a short time within this period. The shoreline dropped *c.* 3 m in less than 200 years, giving a minimum rate of 1.5 cm/year. This drop may mark a distinct end to the Tapes sea level still stand, and is roughly coeval with the timing of retreat of the last remaining ice sheets in northern Canada (Smith *et al.* 2011). One reason for the sudden shoreline drop could be an abrupt end to eustatic sea level rise, due to this termination of the major deglaciation in Canada. Another reason could be tectonic forces, with a sudden and strong acceleration in the rate of land uplift. Changes in the gravitational field of the Earth, causing deformation to the geoid, may also have contributed.

F: 7100–1900 cal years ago
The rate of shoreline displacement stabilized over a long period at *c.* 0.3 cm/year. The curve through this period is almost linear, representing the slow and near stable relaxation of the crust.

G: 1900–1300 cal years ago
Another relatively rapid drop in relative sea level took place during this period in the late Holocene. This

constitutes a marked change after the long stable period F, with a more than doubled regression rate averaging at 0.7 cm/year. The rapid change in relative sea level during both period E and period G was not expected prior to this investigation. However, an accelerated RSL fall roughly coinciding with sub-period G was also suggested in a previous study (Stabell 1980). These are intriguing new results that are well-documented through this study, and they need to be followed up by future work.

H: 1300 cal years ago -present

The last 1300 years are characterized by slow regression of *c.* 0.1 cm/year and no variability is discernible from the new isolation basin data.