Late Weichselian relative sea-level changes and glacial history in Hordaland, Western Norway

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Scientific environment

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Contents

Abstract

Two well dated lateglacial relative sea-level curves have been constructed from Hordaland, western Norway, by the isolation basin method. The easternmost curve is based on six basins from the Os area, close to the Younger Dryas (YD) ice-sheet margin, at a YD isobase of 58 m a.s.l. The western curve was constructed at a site 20 km further west, at a YD isobase of 40 m, and is based on detailed studies of three basins located on the island of Sotra. In addition 22 basins from an earlier conducted study on Sotra have been re-evaluated and calibrated, and the presented curve consists of 43 sea-level index points documenting the complete late- and postglacial sea-level history of Sotra.

A major feature in the lateglacial sea-level history of western Norway is the YD transgression, representing a rise in relative sea level of 10 m. It temporarily reversed the ongoing relative sea-level fall following the deglaciation. The transgression started in late Allerød, 200-300 years before the YD cooling, and culminated in the late YD. The highstand at the YD transgression maximum had duration of about 200 years, and the sea level fell rapidly slightly after the YD/Holocene boundary and the rise in the birch (*Betula*) pollen curve.

The two sea-level curves and marine limit terraces in the area have been used to construct a shoreline diagram with shorelines for the regression minimum in Allerød and the YD transgression maximum. These shorelines have almost parallel tilts of 1.2-1.4 m km^{-1}, indicating that no isostatic tilting, and thus neither uplift nor depression occurred during the sea-level rise. It is concluded that the YD transgression was caused by a major YD ice-sheet advance mapped in the same area. This stopped the isostatic uplift and increased the gravitational attraction on the sea which elevated the geoid in this area. There may also have been a contribution from rising glacio eustatic sea level. The YD transgression started in the late Allerød, thus it is concluded that the YD ice-sheet advance started before the onset of the YD.

Recently, several scientists have postulated that there was no major glacier advance during the YD, based on observations along the Hardangerfjord. If correct, this has consequences for the proposed explanation of the YD transgression, and it is therefore performed a test by dating the large terminal moraine crossing the fjord close to the fjord mouth. The results indicate that the terminal moraine at the mouth of Hardangerfjorden was deposited in mid and late YD (10.6-10.0 kyr ^{14}C BP). It is concluded that the there was a major YD ice-sheet advance in western Norway, also in the Hardangerfjord area.

List of papers

Paper I:

Lohne, Ø.S., Bondevik, S., Mangerud, J. and Schrader, H., 2004. Calendar year age estimates of Allerød - Younger Dryas sea-level oscillations at Os, western Norway. Journal of Quaternary Science 19, 443-464.

Paper II:

Lohne, Ø.S., Bondevik, S., Mangerud, J. and Svendsen, J.I., submitted. The start of a major sea-level rise indicates that ice-sheet expansion in western Norway commenced before the Younger Dryas. Submitted to Quaternary Science Reviews, December 2005.

Authorship statement

The two papers in the present thesis are joint publications. I am the lead author of both papers and have been responsible and conducted most of the work with the papers. This includes field- and laboratory work, picking material for AMS dating, diatom analysis, analysing of data, preparing figures and writing the papers. All of the co-authors have contributed with guidance and suggestions throughout the work from the planning of the project to submission of the papers. The manuscripts have been critically examined by the all respective co-authors and they have contributed with valuable improvements and suggestions to the text. In addition; Stein Bondevik participated in most of the fieldwork; Jan Mangerud participated in the fieldwork at Særvikmyra (Paper I) and Halsnøy (Introduction); John Inge Svendsen participated on the fieldwork at Halsnøy (Introductions); and Hans Schrader provided guidance during the diatom analysis.

Introduction

Objectives

The main objective for the present thesis has been to describe precisely the late glacial sea-level history of western Norway, based on new field evidences. The broad outline of the sea-level and the deglaciation history in western Norway has been known for decades, based on extensive studies 20-40 years ago (e.g. Mangerud, 1970; Anundsen, 1985). Since then there has been an enormous development in the scientific knowledge and methods. Therefore there is a large potential for improvement of the description and understanding of the sea-level and glacial history by collection of new high quality data. The result from the present thesis will increase our knowledge about geological processes during the deglaciation and can be utilized in the reconstruction of the deglaciation history. Further, the outcome of the thesis provides a high quality input for high resolution isostatic modelling which will test our interpretations and potentially provide valuable information on the visco-elastic properties of the crust.

Perspectives

The Quaternary glaciations had a major impact on the sea level. The repeated waxing and waning of the large ice sheets during the Quaternary changed the volume of water stored on land as glacier ice, resulting in fluctuations of the global sea level. The amplitude of potential glacial induced eustatic sea-level change is about 200 m, and currently about 80 m of sea level equivalent water is stored on land as glacial ice (Gray, 1995). Since the last glacial maximum (~20 000 cal. yr BP) the sea level has risen about 130 metres as a result of melting of land-based glacial ice (Lambeck et al., 2002). In the areas occupied by the former ice sheets the relative sea level was also affected by the glacio isostatic depression caused by the load of the ice. In these areas the crustal rebound following the wasting of the ice sheet overdue the eustatic sea-level rise, resulting in a net relative sea-level fall since the deglaciation, as for example in most of Scandinavia. Relative sea-level curves from these areas are mainly a result of interplay between these two components, in addition to changes in geoid (gravitational attraction between land/ice and ocean) and tectonics.

One of the major usages of relative sea-level curves in geosciences is to reconstruct former ice sheets, because the sea-level change close to and within the limits of the former ice sheet is heavily affected by the glacier load on the crust. It is therefore frequently used to model the thickness of ice sheets by isostatic modelling. This is done by combining spatial distributed relative sea-level curves, the glacio eustatic sea-level curve and the physical properties of the crust/mantle. The two former of these can be obtained by observations, but the earth's interior physical properties is not possible to measure. However, where the glacier load can be deduced by other criteria, these properties can be estimated. This method is frequently used, also by geophysicists with primary interest in the crust and mantle structure. In this sense sea-level observations are key input for both isostatic modelling of former ice sheets and models estimating the internal structure of the earth.

Relative sea-level curves are also obviously of great importance for our knowledge of the former coastline, local history and landscape evolution at coastal sites. E.g. knowledge of the sea-level history is essential when reconstructing the run-up height for earlier tsunami events (e.g. Bondevik et al., 2005). Archaeologists also widely use sea-level observations to discover and date prehistoric settlements. It is therefore important to increase our knowledge of the sea-level history by obtaining new sea-level observations.

Presentation of the papers

The two papers included in the present thesis describe two studies that have been conducted in the Bergen area in Western Norway (Fig 1). The main focus of these papers has been on the lateglacial sea-level change, and how the sea-level change relates to the deglaciation history of the area. Two sea-level curves have been outlined and presented; one from the Os area (Paper I: Lohne et al., 2004), and one from the island of Sotra (Paper II: Lohne et al., Submitted). In Paper II the results from both sites have been synthesised and an equidistant shoreline diagram has been constructed.

The relative sea-level curves are based on the so-called isolation basin method (Hafsten, 1960). Cores from isolation basins at different elevations have been investigated. Transitions between marine and lacustrine sediments have been identified by diatom analysis and plant macrofossils from these levels have been radiocarbon dated. The broad outline of the lateglacial sea-level changes in western Norway, including a remarkable relative sea-level rise culminating during the Younger Dryas (YD), was known prior to our investigations (Krzywinski and Stabell, 1978, 1984; Anundsen, 1985). We could therefore select basins for the study at the best suitable elevations, and in both areas we have been able to document both the regression minimum prior to the so-called YD transgression (Anundsen, 1985) and the subsequent transgression maximum, with high precision.

A main challenge when working with lateglacial sediments is to establish a precise chronology (e.g. Lowe et al., 2001). In the present papers the chronologies are mainly based on series of AMS ^{14}C dates of terrestrial plant material, which enable a relative precise transformation to calibrated time scales. In Paper I this has been done by a "wiggle matching" technique (Pearson, 1986; Gulliksen et al., 1998; Blaauw et al., 2004), where the age and sediment accumulation rate has been fitted to the series of dates. The disadvantage of this method is that for archives without independent age control like e.g. tree rings and varves, the time intervals between the dated levels are not known and the sediment accumulation rate has to be assumed constant. Even though the method is used only on dates from the same sedimentary unit, it is obviously a simplification. In Paper II we used a statistical method based on a Bayesian probability technique, which has been recommended for archives without independent age control between dated levels (Blockley et al., 2004; Bronk Ramsey, 2005). This method incorporates prior information about the stratigraphic context and succession of the dates into the analysis (see Paper II). An other difference is that in Paper I we used a combination of the INTCAL98 (Stuiver et al., 1998) and the

Cariaco dataset (Hughen et al., 2000) for calibration, whereas we in Paper II used the INTCAL04 dataset (Reimer et al., 2004). However, this has no influence for the conclusions, but the calibrated age intervals may not be directly comparable.

One of the main outcomes from the papers is that the YD transgression occurred from the late Allerød to late YD. It has been shown that the start of the transgression occurred prior to the climatic deterioration at the Allerød/YD transition. During the YD transgression the sea level rose about 10 m, and the subsequent high stand prevailed across the YD/Holocene boundary and the rise in *Betula* (birch) pollen. The maximum peak of the YD transgression occurred simultaneously with the deposition of the YD terminal moraine and accordingly simultaneous with the maximum extension of the YD ice sheet. However, the high sea level prevailed some time after the initial withdrawal of the ice-sheet margin at the YD/Holocene boundary (Bondevik and Mangerud, 2002).

Overall, the presented relative sea-level curves constitute the hitherto best documented lateglacial sea-level curves from Norway, and describe the sea-level change in western Norway with high precision chronologically and spatially. Therefore, the papers in the present thesis represent one significant step forward in the description and understanding of the YD transgression in western Norway.

In the papers we argue that the cause of the YD transgression is the major YD ice-sheet advance in Western Norway (Mangerud, 1970; Bondevik and Mangerud, 2002). Geophysical modelling also indicate this causal relation (Fjeldskaar and Kanestrøm, 1980; Anundsen and Fjeldskaar, 1983). This implicates that the increased glacial loading of an ice-sheet advance is reflected in the relative sea-level changes, and that sea-level changes potentially can be utilized to date the ice-sheet advance. Glacier advances are often difficult to date by other methods because older sediments often have been removed by the advancing glacier. Our conclusion is that the glacial advance in western Norway that culminated in the late YD, started prior to the start of the relative sea-level rise during the late Allerød.

YD ice-sheet configuration in Hordaland

The YD ice-sheet re-advanced used in the papers to explain the YD transgression advanced more than 50 km (Mangerud, 1977, 2004), and terminated at the Herdla-Halsnøy moraines (Aarseth and Mangerud, 1974; Holtedahl, 1975) late in the YD (Bondevik and Mangerud, 2002). This distinct terminal moraine has been mapped more or less continuously along the coast of Hordaland (Figure 1). It consists of sub-marine ridges, glaciofluvial ice contact deltas and discontinues end and marginal moraines (Anundsen, 1972; Aarseth and Mangerud, 1974; Holtedahl, 1975; Aarseth et al., 1997).

However, several scientists have recently challenged the interpretation given above and postulated that the Hardangerfjorden (Figure 1) remained ice free throughout the entire YD (Helle et al., 1997; Bakke et al., 2000; Helle et al., 2000; Bakke, 2004; Helle, 2004; Bakke et al., 2005). Helle and co-workers argue that they have found the YD transgression described from the coastal areas (Anundsen, 1985; Lohne et al., 2004; Lohne et al., Submitted) both in isolation basins (Helle et al., 1997) and in the ice-contact delta in Eidfjord (Helle, 2004), near the head of the fjord (Figure 1). Bakke and co-workers described cirque moraines in Jondal (Figure 1), and according to their interpretation the corresponding glaciers could not have been of Holocene age because the reconstructed ELA depression was as low as 1160 m below the present situation. They therefore suggested an YD age of these moraines. They also reported ^{14}C dates with ages up to 10 450 ^{14}C BP from basins located in the vicinity of the present glacier Northern Folgefonna (Figure 1), suggesting that this mountain area was deglaciated well before the onset of the Holocene (Bakke et al., 2005). The implication of their hypothesis is that the glacial extension in Hordaland during the YD was radically more restricted than visualized by earlier reconstructions (e.g. Mangerud, 2000). Helle (2004) suggests that the western margin of the inland ice sheet was situated at the head of Hardangerfjorden during the YD (Figure 1), and Bakke et al. (2005) propose that the glacier limit of Northern Folgefonna during the YD was situated slightly (maximum 2 km) outside the margin of the present icecap

(Figure 1). The proposed hypothesis implies that the Hardangerfjorden was deglaciated prior to the YD and that no major re-advance occurred during the YD.

There is a large difference in volume of ice between the conventional and the suggested reconstructions and therefore also a large difference in the load performed on the crust by the ice masses. In the present thesis (Paper I and II) the YD transgression has been explained by combination of increased glacial load on the crust stopping the glacio isostatic uplift and by deformation of the geoid, both these factors as a result of a major YD ice-sheet advance. Our suggested explanation is therefore not compatible with the recently suggested hypothesis.

It was therefore essential to solve the contradiction regarding the glacier extent in Hordaland during the YD, in order to validate if the ice-sheet fluctuation is a likely explanation for the YD transgression. We therefore performed a test of the ice-sheet extent in Hardangerfjorden based on new field observations from the outer Hardangerfjorden area.

The Halsnøy terminal moraine

The Halsnøy terminal moraine is one of the most extensive Quaternary deposits along the coast of Hordaland and is crossing the outer Hardangerfjord in the Huglo-Halsnøy area (Figure 2). It consists of submarine and subaerial marginal moraine complexes forming an arc shaped ridge from Valen to Tysnes (Figure 2). Traditionally this moraine has been interpreted as the southwards continuation of the Herdla moraine (Undås, 1963; Holtedahl, 1967; Follestad, 1972; Holtedahl, 1975; Aarseth et al., 1997; Mangerud, 2000). This interpretation was supported by ^{14}C dates on shells from subtill and till deposits along the fjord (Figure 2) yielding ages in the range of 11 530 – 10 930 ^{14}C yr BP and suggesting a younger ice-sheet advance reaching the outer of Hardangerfjorden area (e.g. Mangerud, 2000). The age of the Huglo-Halsnøy terminal moraine is obviously decisive regarding the ice-sheet extent during YD. If the Hardangerfjord was ice free during the YD the terminal moraine predates the YD.

Otherwise if this terminal moraine is of YD age, Hardangerfjorden was filled by the ice during the YD and the deglaciation of the fjord occurred subsequently.

The terminal moraine makes up much of the north-western part of the island of Halsnøy (Figure 2 and 3). The accumulations are mostly found below the marine limit and are connecting several rocky hills (Figure 3). In the eastern part of Halsnøy the accumulations occur along the northern slopes of the large rocky hill (Figure 2), from the sea level and up to 80 m a.s.l. This is above the marine limit which here is about 70 m a.s.l. (Anundsen, 1985). The contact to the exposed bedrock further uphill appears as a distinct 10-15 m high moraine ridge shown close to the Høylandsundet (Figure 2), indicating that the sediments were deposited from glacier flowing southwards.

Three locations were investigated at Halsnøy (Figure 2 and 3); (i) the Eidesvika outcrop located in the proximal slope of the of the terminal moraine, (ii) the lake Gravdalsvatn, situated in the north-south oriented valley centrally in the southern part of the island, and (iii) the mire, Kjekamyr, located south on Halsnøy about 5 km distally to the moraine.

(i) Eidsvika

An outcrop, about 50 m wide and 2 m high, along the beach in Eidsvika (Figure 4) was investigated the autumn of 2004. The entire outcrop consisted of massive, bluish diamicton with high content of silt and clay (~60%), and with boulders up to 50 cm (Figure 4A and B). The sediment is strongly compacted and almost impossible to dig with shovel. The diamicton contained scattered shell fragments, but no whole valves were found (Figure 4C). Based on the high degree of compaction, lack of stratification and the completely non-sorted particle size distribution the diamicton is confidently interpreted as a till. Shell fragments were carefully picked out from the bluish non-weathered part of the sediments, and six solid fragments, probably of *Mya truncata*, were dated. The dates obtained ages between 11 560 and 10 905 ^{14}C yr BP (Figure 4C, Table 1). These dates provide maximum age for the till deposition and indicate that the terminal moraine at Halsnøy was formed during the YD.

(ii) Gravdalsvatn

The reason for coring the lake Gravdalsvatn (Figure 2) was to find meltwater sediments deposited distally to and contemporary with the terminal moraine across Halsnøy. The valley, has its present water divide slightly north of the lake. When the terminal moraine at Halsnøy was deposited, the northern end of the valley where Gravdalsvatn is situated, was blocked by the glacier and the meltwater had to be routed southwards, through Gravdalsvatn. Three Russian peat cores were obtained from the lake basin. Below the high organic Holocene gyttja only a thin (10 cm) layer of bluish silt was found above the bedrock or till at the bottom of the basin. Except for this thin silt bed, interpreted as deglaciation sediments, no pre-Holocene sediments were found in the basin. The sediments found in Gravdalsvatn therefore postdate the terminal moraine at Halsnøy. We believe that the YD glacier had its absolute maximum extension near the southern end of this lake.

This assumption is supported by the occurrence of a lateral moraine along the western slope of the valley where the lake basin is located (Figure 2). The up to 5 m high morainic ridge could be traced for 250 m and was sloping southwards from 140 to 120 m a.s.l. The orientation of the moraine shows that it has been deposited by a glacier flowing from the north and terminating in the valley somewhere south of Gravdalsvatn.

(iii) Kjekamyr

The motivation for investigating Kjekamyr was, like for Gravdalsvatn, to find and date the ice-proximal glaciomarine deposits that corresponds with the terminal moraine at Halsnøy. Kjekamyr (47 m a.s.l.) is located about 15 m below the marine limit (~62 m a.s.l.) (Anundsen, 1985), and about 5 km distally to the Halsnøy moraine.

The basin is an up to 8 m deep bedrock depression. It is about 300 m long and 70 m wide and is presently occupied by a mire. The drainage area is small (14.9 ha) and is dominated by exposed and vegetation covered bedrock without any notable sediment accumulations. Several sites in the basin were cored by using a Russian peat corer, and the most suitable was selected for coring with a 110-mm modified GEONOR piston corer using 2 m long PVC tubes (core 505-50). The base of the core that did not reach bedrock has been dated to about 12 ka ^{14}C BP (Figure 5). A ^{14}C date that was obtained from a neighbouring core that was collected with a Russian peat sampler shows that the sedimentation in the basin started before 12.4 ka ^{14}C BP (Table 1). The lower 50 cm of core 505-50 consists of silty gyttja with relative high organic content (Figure 5). Fragments of marine shells (mainly *Mytilus edulis*) and high concentration of fragmented kelp show that this is marine sediments. Upwards the organic content decreases, and at 740 cm depth there is a sharp boundary to a bluish grey silt with very low organic content (Figure 5). The silt unit is about 2 m thick and consists of irregularly spaced finely laminated intervals. At 680 cm a distinct peak of ash particles was found in the >63 μm fraction by inspection under stereomicroscope (Figure 5). Judged from the visual characteristics of the glass shards and the stratigraphical position it is interpreted as the Vedde Ash Bed (Mangerud et al., 1984). The upper boundary of the silt unit is sharp and erosional, and is overlain by 25 cm thick normal graded massive marine sand. The distinct sedimentary change at 505 cm depth (Figure 5) has been identified as the isolation contact by diatom analysis. The upper 505 cm consists of lacustrine dark brown gyttja including peat on the top.

The laminated silt is very different from the other sediments in the core, and reflects a distinct change of sedimentation condition in the basin (Figure 5). The colour, irregular laminations, grain size and very low organic content (LOI) are characteristic for glaciomarine sediments deposited in shallow water (e.g. Bondevik and Mangerud, 2002). The ^{14}C dates also show that the sedimentation rate was much higher (~2.0 mm yr^{-1}) compared to the strata below and above (~0.7 mm yr^{-1}). The sediment is therefore interpreted as ice-proximal glaciomarine deposits. The ^{14}C dates and the stratigraphical position of the Vedde Ash Bed (c. 12,000 cal. yr BP), indicate that the glaciomarine sediments accumulated between ca. 10.6-10.0 ^{14}C kyr BP. The glaciomarine silt is correlative with the YD ice-sheet advance that culminated at Halsnøy, and the stratigraphy of Kjekamyr therefore indicates that the terminal moraine at Halsnøy was deposited during the mid and late YD. It is worth mentioning that at Os (Figure 1) the ice sheet reached its outermost position after the Vedde Ash Bed (Bondevik and Mangerud, 2002), whereas the stratigraphy in Kjekamyr indicates that the ice front was close to Halsnøy before the Vedde Ash fall.

The YD ice-sheet extent in Hardangerfjorden

As presented above all the three studied sites indicate that the terminal moraine at Halsnøy is of YD age. The shells from the till and the lake stratigraphy show that the ice front was located at northern Halsnøy, during mid and late YD. The arc shaped form of the moraine and its continuation on the sea floor across the fjord, strongly suggests that the Huglo-Halsnøy moraine accumulated in front of an ice tongue flowing out of the Hardangerfjord and not by glaciers from the mountains nearby. This conclusion is in argument with evidences from adjacent areas; (i) dates from shell-bearing tills along the northwest shores of the fjord (Aarseth and Mangerud, 1974; Mangerud, 2000; Lohne, unpublished dates) and at Valen along the south-east shore of the fjord (Holtedahl, 1967) (Figure 2), (ii) sediments in several lakes on Tysnes showing that parts of Tysnes were occupied by a glacier flowing from Hardangerfjorden during the late YD (Lohne, in prep), (iii) dates of the deglaciation in Tørvikbygd (Romundset, 2005).

The presented observations are not compatible with the assumption that Hardangerfjorden was ice free during the YD (Helle et al., 1997; Helle, 2004; Bakke et al., 2005). However, common for all the studies arguing for an ice free Hardangerfjord during the YD is that the interpreted chronology may be questioned, because they are based on undated (delta and cirque moraine) or poorly dated (bulk ^{14}C dates) observations. Mangerud (2000) has previously criticised the chronological interpretations by Helle et al. (1997). In a more recent study Bakke et al. (2005) argue that three ^{14}C dates (10 450, 10 200, and 10 200 ^{14}C BP) from three different cores obtained form two lake basins in Jondal area, support the interpretations by Helle et al. (1997). However, all three are bulk sediment dates on basal sediments with low (<5%) organic content. Such dates have been known to frequently give too high ages due to a content of “old” carbon even if the surrounding bedrocks are almost carbon-free (Sutherland, 1980). Thus, there are no trustworthy dates inside the Halsnøy-Huglo moraine that suggests that Hardangerfjorden was ice free during YD.

One should also bear in mind that one single stratigraphical sequence, with unquestionable, lateglacial chronology like e.g. Kjekamyr (Figure 5), found inside the Huglo-Halsnøy terminal moraine, would falsify the conventional YD ice-sheet model. No such site has been reported, even though a significant number of basins have been studied (Anundsen and Simonsen, 1967; Helle et al., 1997; Bakke et al., 2005; Romundset, 2005; unpublished study by Lohne, Mangerud and Svendsen). I therefore consider it proven beyond reasonable doubt, that the inland ice sheet occupied the Hardangerfjord and terminated at the Huglo-Halsnøy moraine during the YD. (Bondevik et al., 1999)

References

Anundsen, K., 1972. Glacial chronology in parts of southwestern Norway. Norges geologiske undersøkelse 280, 1-24.

Anundsen, K., 1985. Changes in shore-level and ice-front position in Late Weichsel and Holocene, southern Norway. Norsk geografisk Tidsskrift 39, 205-225.

Anundsen, K. and Fjeldskaar, W., 1983. Observed and theoretical Late Weichselian shore level changes related to glacier oscillations at Yrkje, southwest Norway. In: H. Schroeder-Lanz (Ed.), Late- and Postglacial Oscillations of glaciers: Glacial and periglacial forms. A. A. Balkema, Rotterdam, 133-170.

Anundsen, K. and Simonsen, A., 1967. Et preborealt brefremstøt på Hardangervidda og i området mellom Bergensbanen og Jotunheimen. Årbok for Universitetet i Bergen, Mat.-nat. serie 7, 1-42.

Bakke, J., 2004. Late Weichselian and Holocene glacier fluctuations along a south-north coastal transect in Norway. Dr. scient. thesis, University of Bergen (22 pp).

Bakke, J., Dahl, S.O. and Nesje, A., 2000. Reconstructions of Younger Dryas and Holocene glacier fluctuations and paleoclimate at Folgefonna, southwestern Norway. Geonytt 1-2000, 36.

Bakke, J., Dahl, S.O. and Nesje, A., 2005. Lateglacial and early Holocene palaeoclimatic reconstruction based on glacier fluctuations and equilibrium-line altitudes at northern Folgefonna, Hardanger, western Norway. Journal of Quaternary Science 20, 179-198.

Blockley, S.P.E., Lowe, J.J., Walker, M.J.C., Asioli, A., Trincardi, F., Coope, G.R., Donahue, R.E. and Pollard, A.M., 2004. Bayesian analysis of radiocarbon chronologies: examples from the European Late-glacial. Journal of Quaternary Science 19, 159-175.

Blaauw, M., Heuvelink, G.B.M., Mauquoy, D., van der Plicht, J. and van Geel, B., 2004. A numerical approach to 14C wiggle-match dating of organic deposits: best fits and confidence intervals. Quaternary Science Reviews 22, 1485-1500.

Bondevik, S., Birks, H.H., Gulliksen, S. and Mangerud, J., 1999. Late Weichselian Marine 14-C reservoir ages at the western coast of Norway. Quaternary Research 52, 104-114.

Bondevik, S. and Mangerud, J., 2002. A calendar age estimate of a very late Younger Dryas ice sheet maximum in western Norway. Quaternary Science Reviews 21, 1661-1676.

Bondevik, S., Mangerud, J., Dawson, S., Dawson, A. and Lohne, Ø., 2005. Evidence for three North Sea tsunamis at the Shetland Islands between 8000 and 1500 years ago. Quaternary Science Reviews 24, 1757-1775.

Bronk Ramsey, C., 2005. The OxCal radiocarbon calibration software, v3.10.

Fjeldskaar, W. and Kanestrøm, R., 1980. Younger Dryas geoid-deformation caused by deglaciation in Fennoscandia. In: N.-A. Mörner (Ed.), Earth rheology, isostasy and eustasy. John Wiley & Sons, Chichester, United Kingdom, 569-574.

Follestad, B.A., 1972. The deglaciation of the South-Western part of the Folgefonn Peninsula, Hordaland. Norges geologiske Undersøkelse 280, 31-64.

Gray, J.M., 1995. Glacio-isostasy, glacio-eustasy and relative sea-level change. In: J. Menzies (Ed.), Past glacial environments: Sediments, forms and techniques. Butterworth-Heinemann, Oxford, 315-333.

Gulliksen, S., Birks, H.H., Possnert, G. and Mangerud, J., 1998. A calendar age estimate of the Younger Dryas-Holocene boundary at Kråkenes, Western Norway. The Holocene 8, 249-259.

Hafsten, U., 1960. Pollen-analytic investigations in South Norway. In: O. Holtedahl (Ed.), Geology of Norway. Norges geologiske Undersøkelse, Oslo, 434-462.

Helle, S.K., 2004. Sequence stratigraphy in a marine moraine at the head of Hardangerfjorden, western Norway: evidence for a high-frequency relative sea-level cycle. Sedimentary Geology 164, 251-281.

Helle, S.K., Anundsen, K., Aasheim, S. and Haflidason, H., 1997. Indications of a Younger Dryas marine transgression in inner Hardanger, West Norway. Norsk geologisk Tidsskrift 77, 101-117.

Helle, S.K., Rye, N. and Stabell, B., 2000. Shoreline displacement and fault activity in the Hardangerfjord, western Norway, after the deglaciation. Geonytt 1-2000, 82.

Holtedahl, H., 1967. Notes on the formation of fjords and fjord-valleys. Geografiska Annaler Series A: Physical Geography. 49, 188-203.

Holtedahl, H., 1975. The geology of the Hardangerfjord, West Norway. Norges geologiske Undersøkelse 323, 1-87.

Hughen, K.A., Southen, J.R., Lehman, S.J. and Overpeck, J.T., 2000. Synchronous radiocarbon and climate shifts during the last deglaciation. Science 290, 1951-1954.

Krzywinski, K. and Stabell, B., 1978. Senglasiale undersøkelser på Sotra. Arkeo 1978:1, 27-31.

Krzywinski, K. and Stabell, B., 1984. Late Weichselian sea-level changes at Sotra, Hordaland, Western Norway. Boreas 13, 159-202.

Lambeck, K., Esat, T.M. and Potter, E.K., 2002. Links between climate and sea levels for the past three million years. Nature 419, 199-206.

Lohne, Ø.S., Bondevik, S., Mangerud, J. and Schrader, H., 2004. Calendar year age estimates of Allerød - Younger Dryas sea-level oscillations at Os, western Norway. Journal of Quaternary Science 19, 443-464.

Lohne, Ø.S., Bondevik, S., Mangerud, J. and Svendsen, J.I., Submitted. The start of a major sea-level rise indicates that ice-sheet expansion in western Norway commenced before the Younger Dryas. Quaternary Science Reviews.

Lowe, J.J., Hoek, W.Z. and INTIMATE-group, 2001. Inter-regional correlation of palaeoclimatic records for the Last Glacial-Interglacial Transition: a protocol for improved precision recommended by the INTIMATE project group. Quaternary Science Reviews 20, 1175-1187.

Mangerud, J., 1970. Late Weichselian vegetation and ice-front oscillations in the Bergen district, Western Norway. Norsk geografisk Tidsskrift 24, 121-148.

Mangerud, J., 1977. Late Weichselian marine sediments containing shells, foraminifera, and pollen, at Ågotnes, Western Norway. Norsk geologisk Tidsskrift 57, 23-54.

Mangerud, J., 2000. Was Hardangerfjorden, western Norway, glaciated during the Younger Dryas? Norsk geologisk Tidsskrift 80, 229-234.

Mangerud, J., 2004. Ice sheet limits on Norway and the Norwegian continental shelf. In: J. Ehlers and P. Gibbard (Eds.), Quaternary Glaciations - Extent and Chronology. Vol 1. Europe. Elsevier, Amsterdam, 271-294.

Mangerud, J., Lie, S.E., Furnes, H., Kristiansen, I.L. and Lømo, L., 1984. A Younger Dryas Ash Bed in Western Norway, and its possible correlations with tephra in cores from the Norwegian Sea and the North Atlantic. Quaternary Research 21, 85-104.

Pearson, G.W., 1986. Precise calendrical dating of known growth-period samples using a "curve fitting" technique. Radiocarbon 28, 292-299.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J. and Weyhenmeyer, C.E., 2004. IntCal04 Terrestrial Radiocarbon Age Calibration, 0-26 Cal Kyr BP. Radiocarbon 46, 1029-1058.

Romundset, A., 2005. Strandforskyvning og isavsmelting i midtre Hardanger. Master thesis, University of Bergen (74 pp).

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J. and Spurk, M., 1998. INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. Radiocarbon 40, 1041-1083.

Sutherland, D.G., 1980. Problems of Radiocarbon Dating Deposits from Newly Deglaciated Terrain: Examples from the Scottish Lateglacial. In: J.J. Lowe, J.M. Gray and J.E. Robinson (Eds.), Studies in the lateglacial of North-West Europe. Pergamon Press, Oxford, 139-149.

Undås, I., 1963. Ra-morenen i Vest-Norge. J. W. Eide, Bergen (78 pp).

Aarseth, I., Austbø, P.K. and Risnes, H., 1997. Seismic stratigraphy of Younger Dryas ice-marginal deposits in western Norwegian fjords. Norsk geologisk Tidsskrift 77, 65-85.

Aarseth, I. and Mangerud, J., 1974. Younger Dryas end moraines between Hardangerfjorden and Sognefjorden, Western Norway. Boreas 3, 3-22.

Table 1 Radiocarbon dates from the investigated sites Eidsvika (59°47.5′N, 5°41.1′E) and Kjekamyr (59°44.3′N, 5°45.0′E) at Halsnøy. Dates of marine material have been corrected for marine reservoir age of 380 years (Bondevik et al., 1999). The calibration of dates is performed with the calibration software OxCal v3.10 (Bronk Ramsey, 2005) and the INTCAL 04 dataset (Reimer et al., 2004).

Locality	Core/ sample	Depth (cm)	Material dated (TPM – terrestrial plant material, MM – marine mussel)	Laboratory number	^{14}C age (yr BP)	Calibrated age (2σ BP)
Eidsvika	04-01	-	MM: Fragments of probably *Mya truncata*.	LuS-5951	10 905 ± 80	13 030 – 12 790
Eidsvika	04-01	-	MM: Fragments of probably *Mya truncata*.	LuS-5952	11 560 ± 70	13 600 – 13 260
Eidsvika	04-01	-	MM: Fragments of probably *Mya truncata*.	LuS-5953	11 015 ± 80	13 100 – 12 850
Eidsvika	04-01	-	MM: Fragments of probably *Mya truncata*.	LuS-5954	11 230 ± 80	13 260 – 12 950
Eidsvika	04-01	-	MM: Fragments of probably *Mya truncata*.	LuS-5955	11 200 ± 70	13 230 – 12 940
Eidsvika	04-01	-	MM: Fragments of probably *Mya truncata*.	LuS-5956	11 085 ± 80	13 150 – 12 870
Kjekamyr	505-137	555-560	MM: Fragments of *Mytilus edulis*.	LuS-5950	12 405 ± 70	14 900 – 14 100
Kjekamyr	505-50-02	812.5-811.5	MM: Fragments of *Mytilus edulis*.	LuS-5949	11 990 ± 70	14 020 – 13 710
Kjekamyr	505-50-02	778.5-777.5	MM: Fragments of *Mytilus edulis*.	LuS-5948	11 485 ± 80	13 540 – 13 180
Kjekamyr	505-50-02	753.5-755.5	TPM: Leaf fragments (*Salix herbacea*, *S. polaris*). Twig. Bud scale.	LuS-5946	11 195 ± 160	13 350 – 12 850
Kjekamyr	505-50-02	748.5-747.5	TPM: Leaf fragments. Mosses (*Polytricum*).	LuS-5945	10 750 ± 70	12 880 – 12 660
Kjekamyr	505-50-02	743.5-741.5	TPM: Leaf fragments (*Salix herbacea*). Mosses (*Polytricum*, *Racomitrium*).	LuS-5944	10 645 ± 100	12 900 – 12 350
Kjekamyr	505-50-02	730.5-728.5	TPM: Leaf fragments (*Salix herbacea*). Mosses (*Polytricum*).	LuS-5943	10 560 ± 60	12 790 – 12 380
Kjekamyr	505-50-01	543.5-542.5	TPM: Mosses (*Racomitrium*). Leaf fragments. Catkin scale.	LuS-5941	9865 ± 70	11 610 – 11 170
Kjekamyr	505-50-01	540.5-539.5	TPM: Mosses (*Racomitrium*).	LuS-5940	10 120 ± 60	12 000 – 11 400
Kjekamyr	505-50-01	520.5-518.5	TPM: Twig. Fruit (Betula). Catkin scale.	LuS-5939	9905 ± 100	11 800 – 11 150
Kjekamyr	505-50-01	506.5-504.5	TPM: Mosses (*Racomitrium*, *Polytricum*). Leaf fragments.	LuS-5938	9950 ± 400	12 850 – 10 350
Kjekamyr	505-50-01	498.5-496.5	TPM: Fruit (Betula). Catkin scale. Twig. Mosses (*Racomitrium*).	LuS-5937	9520 ± 60	11 100 – 10 600

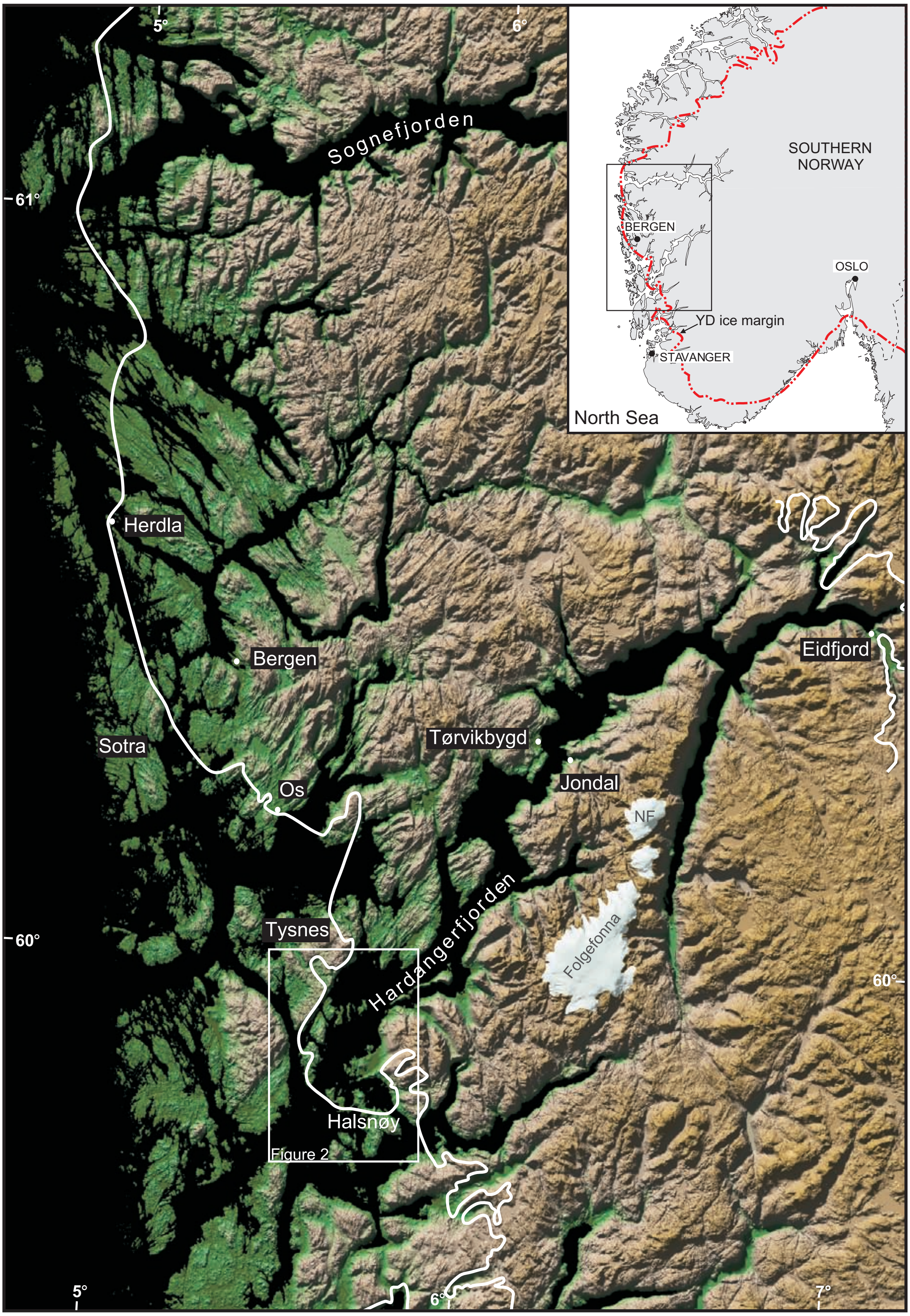

Figure 1 Shaded elevation model of Hordaland County, western Norway, with the YD Herdla-Halsnøy moraines (Anundsen, 1972; Follestad, 1972; Aarseth and Mangerud, 1974). An alternative (Eidfjord-Osa moraine), proposed by Helle (2004) is shown at the head of the Hardangerfjord. NF - Northern Folgefonna.

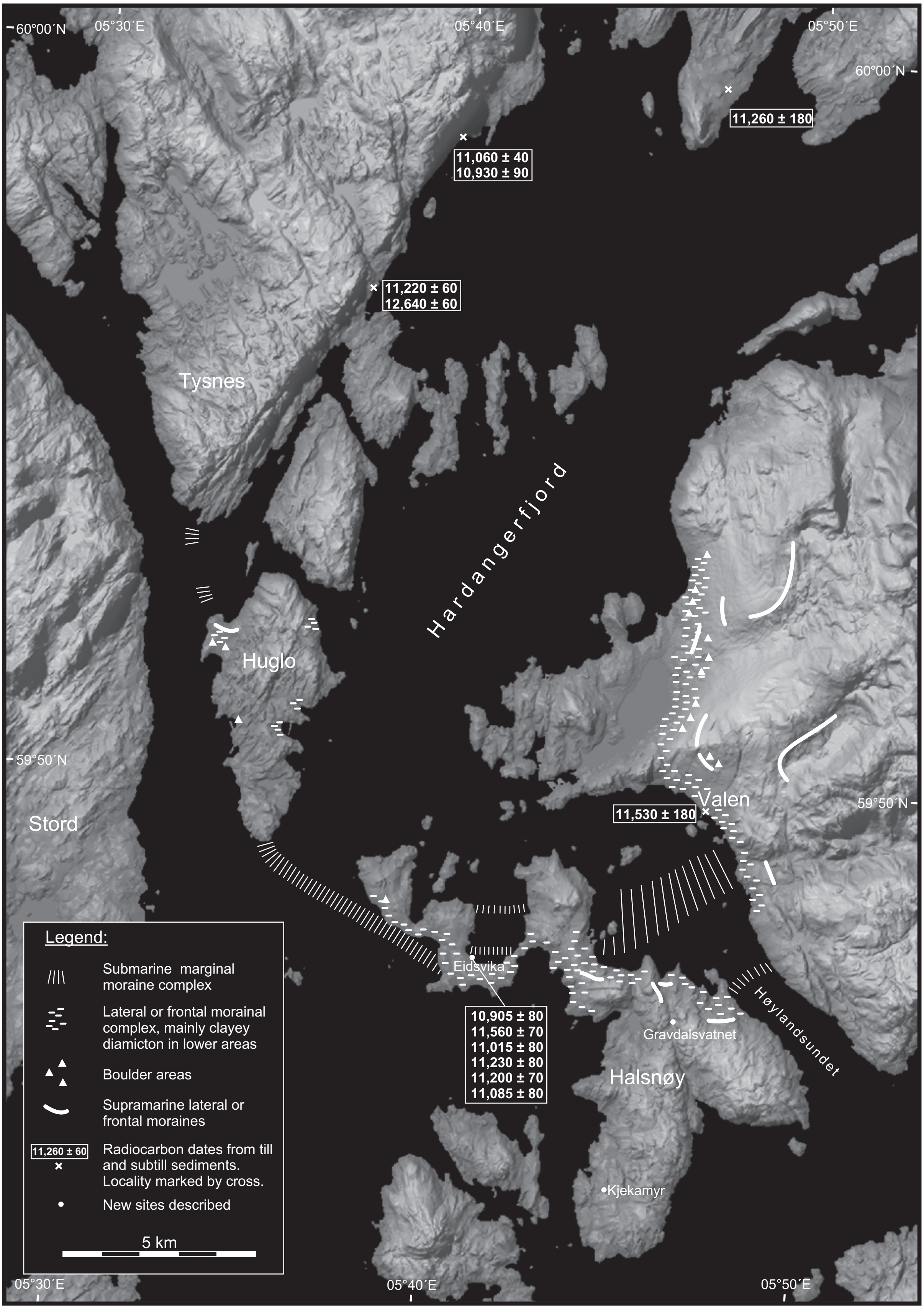

Figure 2 Shaded elevation model of the outer Hardangerfjord area showing the Huglo-Halsnøy moraine. Terrestrial moraines are from Follestad (1972) and Holtedahl (1975), submarine moraines from Aarseth et al. (1997). Dates listed from north to south are from Aarseth and Mangerud (1974), Mangerud (2000), Lohne (unpublished data), Holtedahl (1967) and the present study.

Figure 3 Oblique aerial photograph of Halsnøy seen from the west. The arc shaped moraines (farm land) partly modified during emergence connects several rocky hills (covered with forest). Photo: http://www.nortrike.net.

Figure 4 Photo of the section at Eidesvika, Halsnøy (A and B). The shovel is about 1 m long. The diamicton contained scattered small shell fragments, and six of these have been radiocarbon dated (C). For details about the dates see Table 1.

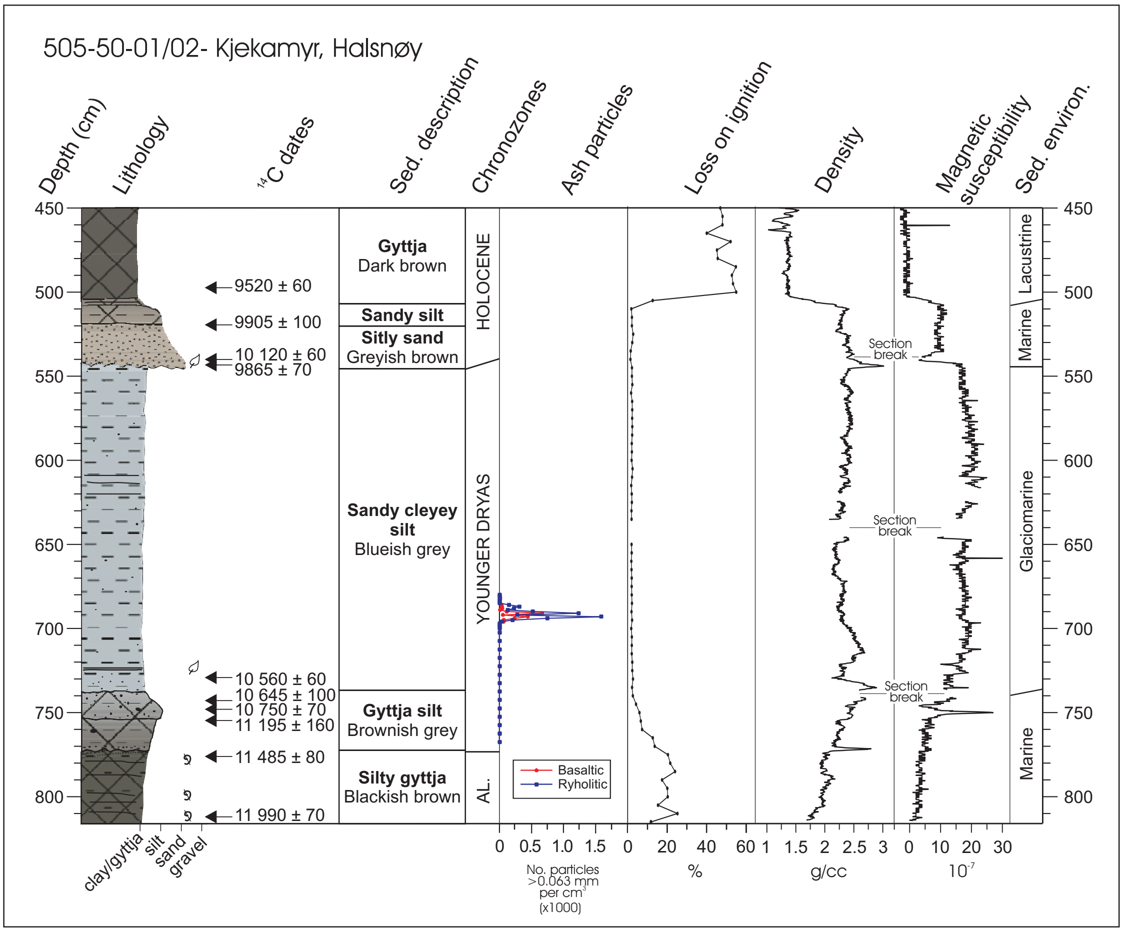

Figure 5 The stratigraphy of core 505-50 collected from the basin Kjekamyr, Halsnøy. The dates are of terrestrial plant remains except the two lowermost which are of marine mussels. For details about the dates see Table 1.