Sea-level changes and pollen stratigraphy on the outer coast of Sunnmøre, western Norway

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The sea-level history for the outermost coast of Sunnmøre was recorded by studying the litho- and palynomorph stratigraphy in eight palaeo-lakes. Deglaciation occurred around 12,600 BP and was followed by a rapid emergence. Then, during the late Allerød and Younger Dryas there was a long-lasting stillstand. This suggests a slow and even eustatic sea-level rise of less than 10 m during this time. A subsequent emergence started with the onset of the Holocene climatic amelioration around 10,200 BP. Radiocarbon dates from the Holocene were obtained from only one basin. The dates from this basin indicate that the Tapes transgression culminated before 8000 BP; however, many dates from neighbouring areas suggest a culmination around 6000–7000 BP. The Late Weichselian pollen stratigraphy has been subdivided into four assemblage zones which can easily be correlated with established zones for the Ålesund area. These include: *Rumex/Oxyria* (12,600–12,000 BP), *Betula–Empetrum* (12,000–11,000 BP), *Salix–Artemisia* (11,000–10,200 BP) and *Betula–Juniperus–Empetrum* assemblage zones. Climatic changes instigated the changes in vegetation associated with these zone boundaries.

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This paper presents a relative sea-level curve for Leinøy based on the litho- and pollen stratigraphy from eight palaeo-lakes situated to the southwest of Ålesund, western Norway (Fig. 1) (Svendsen 1985). The study forms part of an investigation of sea-level changes in Sunnmøre and partly relies on previous work in the Ålesund area (Mangerud et al. 1984; Lie et al. 1983; Kristiansen et al. 1988). The objective was to extend the database as far west as possible, to where the glacio-isostatic uplift was minimal in order to describe the sea-level changes along a cross section of the coast (Svendsen & Mangerud 1987). The pollen stratigraphy diagrams were used primarily for biostratigraphical correlation. They were, however, also used to reconstruct the vegetational history of the area.

The study area includes the islands of Gurskøy, Leinøy and Bergsøy (Fig. 1). The cored basins are situated on the uneven strandflat which encircles the central mountainous part of these islands. The bedrock consists of gneisses (Gjelsvik 1951) partly covered by a thin and patchy veneer of till. All the studied basins – with the exception of Litlevatn and Dalevatn, which are still lakes – are bogs which are completely filled in with Holocene organic sediments.

Methods

The sea-level curve was constructed according to the classical Scandinavian method which relies on the stratigraphy in emerged lake basins situated at different elevations (Fig. 3 in Svendsen & Mangerud 1987). First a Russian peat sampler was used to map the lithostratigraphic units across each basin and to locate appropriate coring sites. Then samples for laboratory investigations were collected with a piston corer with a diameter of 110 mm, which provided up to 2 m long core sections.

The age of the sea level corresponding to the elevation of the outlet of each basin is determined by identifying and dating the transition between brackish and lacustrine beds in the cores. In this area these boundaries (isolation contacts) coincide with major lithological transitions (Lie et al. 1983) and were determined visually and confirmed by means of pollen (phytoplancton) and diatom analysis.

The chronostratigraphic terminology used in this paper follows Mangerud et al. (1974), who defined chronozones in radiocarbon years.

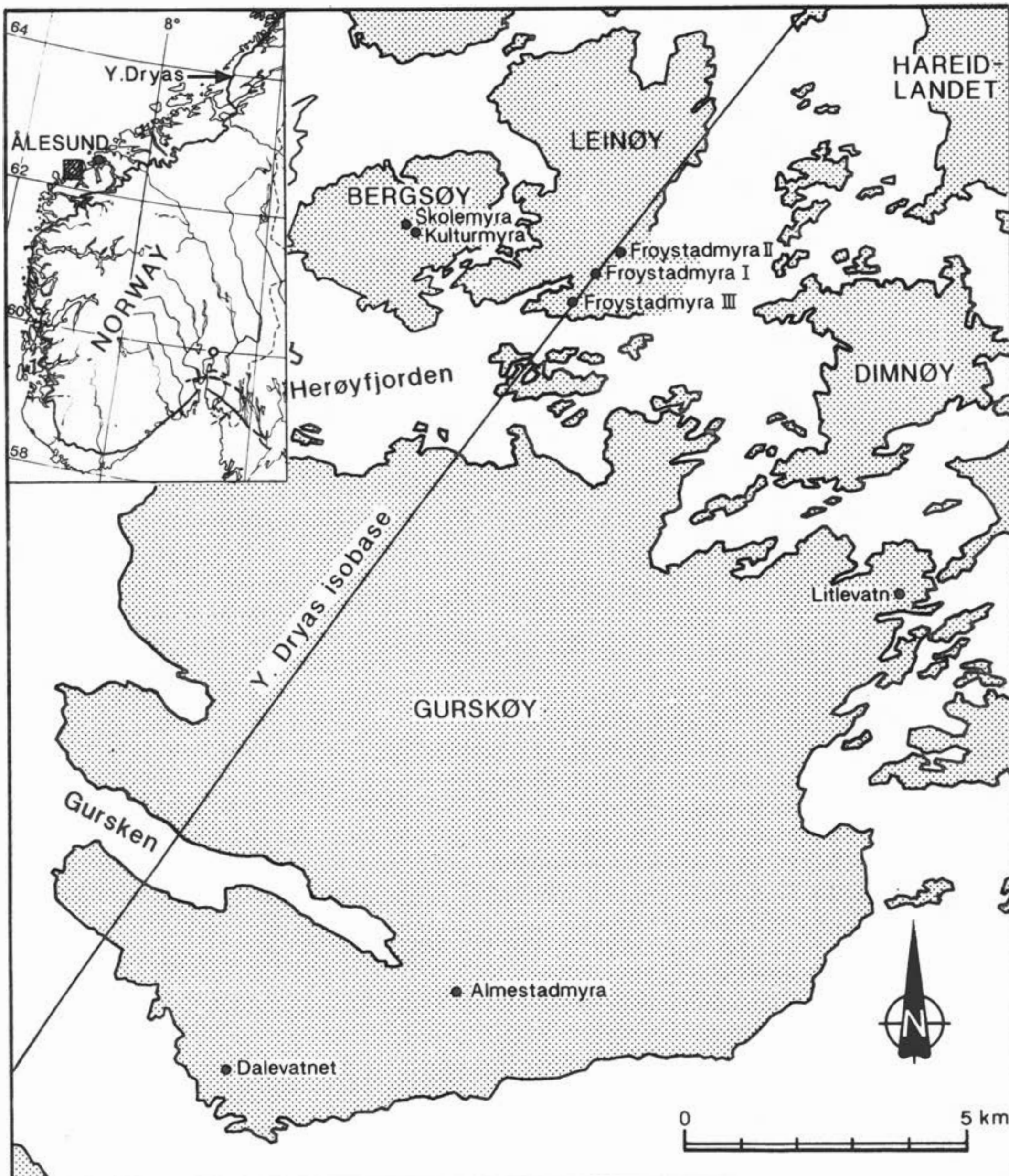


Fig. 1. Location map of the study area with a key map of southern Norway. The investigated sites are marked with dots. The Younger Dryas isobase through Frøystadmyra I, II and III is indicated.

Radiocarbon dates

The radiocarbon dates (Table 1) were carried out at the Radiological Dating Laboratory, Trondheim under the supervision of Reidar Nydal and Steinar Gulliksen. Samples of lacustrine gyttja from directly above the isolation contact were dated to obtain the time of emergence of the lakes. To avoid contamination from penetrating roots from submerged plants (Kaland et al. 1984) only the NaOH-soluble fraction was used (A after the lab. no.). The errors due to the thickness of

Table 1. Radiocarbon dates from the basins presented in this paper. A after the lab. no. means that the NaOH-dissolved fraction is dated. ^{13}C values are given in the PDB scale. All samples are corrected for isotopic fractionation to $^{13}C = -25‰$. The marine shells are corrected for a reservoir age of 440 years. The marine and brackish sediments are not corrected for reservoir age, because the proportion of terrestrial to marine organic matter is unknown; see discussion in text.

Basin	Lab. no.	^{14}C-yr BP	^{13}C	Material	Depth (cm)
Frøystadmyra I	T-8185 A	8,140 ± 110	−23.4	lacustr. gyttja	487–490
Frøystadmyra I	T-4967 A	8,480 ± 160	−27.8	lacustr. gyttja	491–493
Frøystadmyra I	T-4966 A	10,510 ± 190	−20.3	brackish sed.	492–496
Frøystadmyra I	T-4969 A	10,980 ± 160	−20.2	brackish sed.	530–533
Frøystadmyra II	T-4968 IIA	12,410 ± 180	−20.6	lacustr. gyttja	524–527
Frøystadmyra III	T-5146 A	12,220 ± 370	−21.4	lacustr. gyttja	766–770
Kulturmyra	T-5145 A	10,500 ± 140	−20.9	lacustr. gyttja	563–566
Kulturmyra	T-5149 A	13,020 ± 270	−25.7	marine sed.	822–827
Kulturmyra	T-5150	12,530 ± 240	+1.0	marine shells	810–820
Skolemyra	T-5147 A	12,090 ± 200	−21.0	lacustr. gyttja	562–565
Litlevatn	T-5148 A	11,510 ± 120	−20.9	lacustr. gyttja	719–723

sediment slices used for radiocarbon dates (2–4 cm) were considered to be in the order of 50–100 years as estimated from a sedimentation rate of 0.3–0.5 mm yr^{-1}. All samples, with the exception of T-4967 A and T-8185 A from Frøystadmyra I, give reasonable ages compared with well-dated stratigraphical levels, like the Vedde Ash Bed (Mangerud et al. 1984) and the Allerød/Younger Dryas and the YD/Preboreal transitions (Kristiansen et al. 1988). The two unsupported dates from the Holocene gyttja in Frøystadmyra I are discussed later.

For one sample from Kulturmyra (T-5150), fragments of marine shells were dated and corrected for a marine reservoir age of 440 years (Mangerud & Gulliksen 1975). In addition to this shell date, one sample of marine sediments from this core (T-5149 A) and two other sediment samples of a brackish origin from Frøystadmyra I (T-4969 A and T-4966 A) were dated. The gyttja dates should be corrected for a reservoir age corresponding to their content of marine components. The first-mentioned sample was taken from a level 2–7 cm below the dated shells. The difference between these two dates is only 50 years when the gyttja date is corrected for a similar marine reservoir age of 440 years. On the other hand, the samples of brackish origin from Frøystadmyra I both gave expected ages according to the litho- and pollenstratigraphy. Probably most of the organic material in these samples is of lacustrine and/or terrestrial origin.

The sediment sequences were correlated by means of pollen-, litho- and tephra stratigraphy, which provided independent control for evaluating the consistency of the radiocarbon dates.

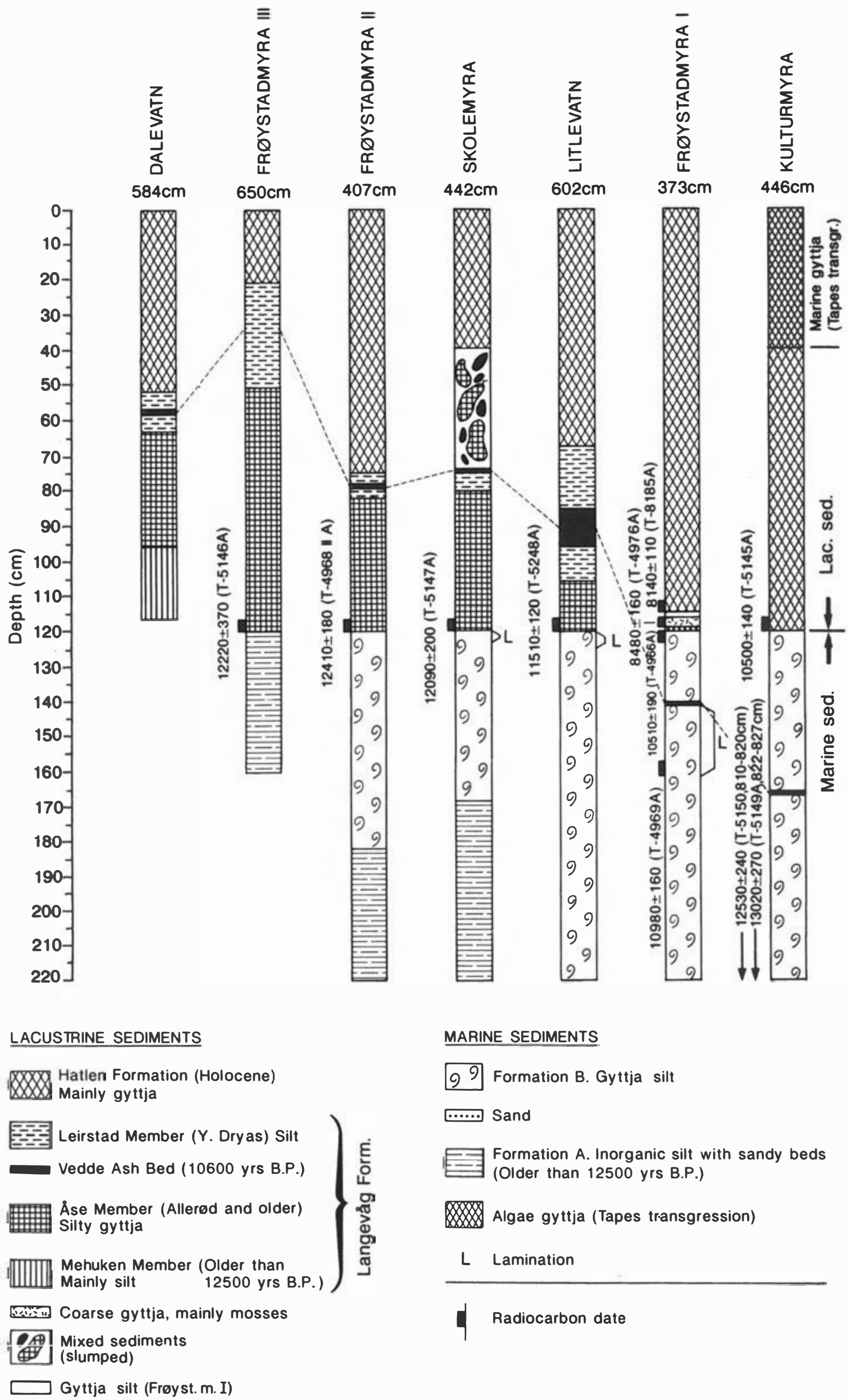
Pollen analysis and diagrams

The sediment samples for pollen analysis were taken as a known volume of wet sediments and Lycopodium tablets (Stockmarr 1971) were added. An influx diagram has been constructed (Svendsen 1985), but is not presented in this paper. The preparation procedures included standard acetolysis and HF treatments, and the identification procedures used are provided in Kristiansen et al. (1988).

A pollen diagram for most of the Late Weichselian is constructed from the lacustrine sediments in Frøystadmyra II (Fig. 5). From the other basins only short sediment sequences around the marine/lacustrine boundaries were analysed.

The number of pollen grains counted (sum P) was between 200 and 500. This pollen sum includes all pollen except for the limnophytes. The palynomorphs not included in the sum P are calculated as the percentage of sum pollen + the actual palynomorph.

In the pollen samples the occurrence of freshwater green algae (*Pediastrum, Botryococcus* and *Tetrahedron minimum*) and marine dinoflagellate cysts ('Hystrix') was noted and used to determine the marine/lacustrine transitions, as shown in the pollen diagrams. There is invariably a distinct flourishing of the green algae directly above the isolation contact, whereas dinoflagellate cysts were rare.



DALEVATN
584cm
FRØYSTADMYRA III
650cm
FRØYSTADMYRA II
407cm
SKOLEMYRA
442cm
LITLEVATN
602cm
FRØYSTADMYRA I
373cm
KULTURMYRA
446cm
Depth (cm)
12220±370 (T-5146A)
12410±180 (T-4968 II A)
12090±200 (T-5147A)
11510±120 (T-5248A)
8480±160 (T-4976A)
8140±110 (T-8185A)
10510±190 (T-4966A)
10980±160 (T-4969A)
10500±140 (T-5145A)
12530±240 (T-5150,810-820cm)
13020±270 (T-5149A,822-827cm)
Marine gyttja (Tapes transgr.)
Lac. sed.
Marine sed.
L
LACUSTRINE SEDIMENTS
Hatlen Formation (Holocene) Mainly gyttja
Leirstad Member (Y. Dryas) Silt
Vedde Ash Bed (10600 yrs B.P.)
Åse Member (Allerød and older) Silty gyttja
Mehuken Member (Older than 12500 yrs B.P.) Mainly silt
Langevåg Form.
Coarse gyttja, mainly mosses
Mixed sediments (slumped)
Gyttja silt (Frøyst. m. I)
MARINE SEDIMENTS
Formation B. Gyttja silt
Sand
Formation A. Inorganic silt with sandy beds (Older than 12500 yrs B.P.)
Algae gyttja (Tapes transgression)
L Lamination
Radiocarbon date

Diatoms

Diatom analysis from a few key beds in five of the basins was carried out by Bjørn Helge Sætersmoen, University of Bergen (Svendsen 1985). The results (not presented in this paper) were used to check the determination of the marine/lacustrine transition.

Lithostratigraphy

The stratigraphy from the cores is shown in Fig. 2. With the exception of Almestadmyra, the lithostratigraphy in these basins has been subdivided into formations and members as defined by Kristiansen et al. (1988). Formations A and B are marine/brackish sediments, whereas the Langevåg and Hatlen Formations are lacustrine sediments. The Langevåg Formation is subdivided into three members: Mehuken Åse and Leirstad. An important marker horizon is the Vedde Ash Bed (10,600 ± 60 BP) (Mangerud et al. 1984), which occurs in both marine and lacustrine strata. A general description of the lithostratigraphic units is given below. The lithostratigraphy of Almestadmyra is described in the section that discusses the individual basins.

Formation A. This formation comprises the lowermost marine sediments and is underlain by bedrock or till (Fig. 2). The sediment consists mainly of grey silt with sandy beds in the lower part. A low organic content is shown by a loss on ignition of lower than 2%. Macrofossils are not found. The formation was most probably deposited in a cold marine environment soon after deglaciation, which in this area is dated to around 12,600 BP.

Formation B. This unit is a brownish grey to grey gyttja silt. The main difference from the underlying formation A is a higher organic content. Marine shells occur frequently, and the presence of *Mytilus edulis* and *Modiola modiolus* from the base of the formation indicate a warmer environment. Two radiocarbon dates from Kulturmyra suggest an age of around 12,600 BP (Table 1) for the base of the formation. In marine beds from the Younger Dryas (Frøystadmyra I, Kulturmyra and several other lakes in the Ålesund area) there is a marked increase of pebbles compared to the sediments of Allerød age. The pebbles were probably dropped from sea ice.

Well-defined red, red-brown and green lamina occur in the upper part of Formation B in Frøystadmyra I, Litlevatn and Skolemyra (Fig. 3). These strongly coloured lamina are typical of a brackish environment in this type of basin (Kristiansen et al. 1988; Krzywinski & Stabell 1984).

The Langevåg Formation. This lacustrine formation has been found in all basins except Frøystadmyra I, Kulturmyra and Almestadmyra, which where all isolated from the sea after its formation (Fig. 2). The Mehuken Member was only found in Dalevatn, which is located above the marine limit and therefore has only lacustrine sediments. This member is characterized by a very low content of organic matter and was deposited

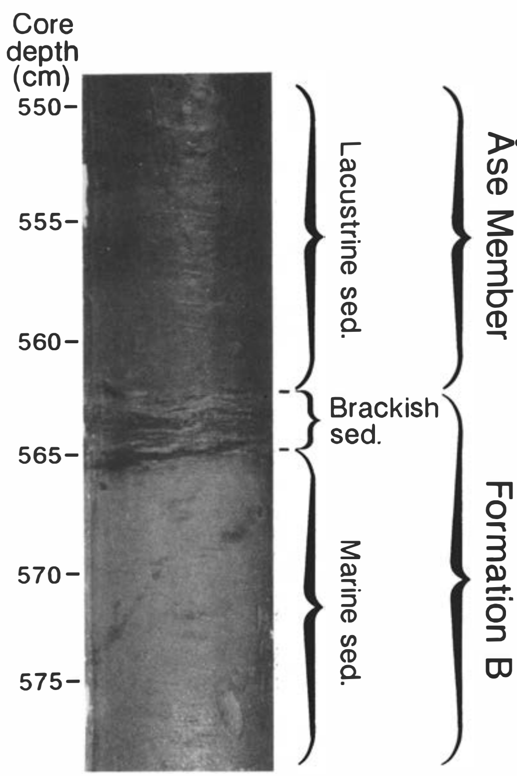


Fig. 3. Photograph of the marine/lacustrine boundary in Skolemyra. Note the lamination at the top of formation B.

Fig. 2. Lithostratigraphic successions and radiocarbon dates obtained from the studied basins. On top of each core segment the depth below the sediment surface for that particular core is given.

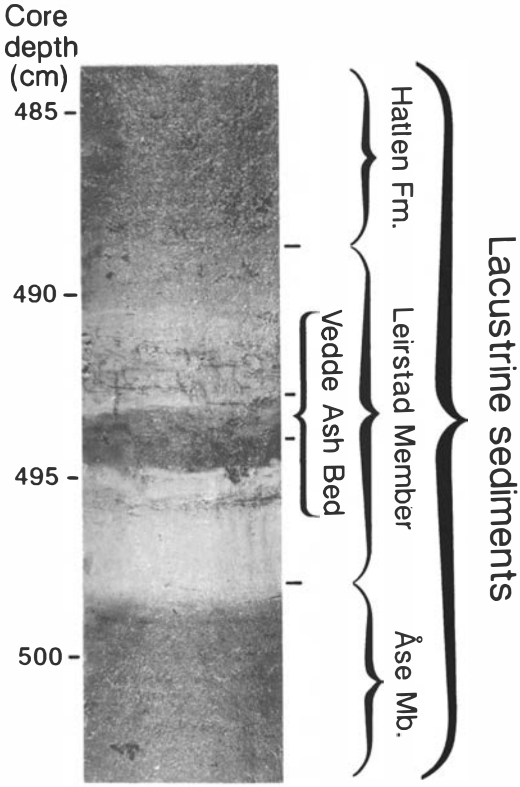


Fig. 4. Photograph of the Leirstad Member in Frøystadmyra II.

contemporaneously with the marine Formation A. The Åse Member is a brownish silty algae gyttja and the Leirstad Member is a light grey silt (Fig. 4). The Leirstad Member was deposited during the Younger Dryas and the boundaries are considered to be isochronous within the area. The Vedde Ash Bed is found near the centre of the Leirstad Member.

The Hatlen Formation. In the lower part, the sediments consist of a light brown, fine detritus gyttja and this gradually becomes darker and coarser upwards. The boundary between the Leirstad Member and the Hatlen Formation occurs at the same level as the distinct rise in the Betula curves. In this study this boundary is assigned the minimum age of 10,200 BP. However, a basal date from the Hatlen Formation (T-5145 A) in Kulturmyra (Table 1) together with similar dates from the Ålesund area (Kristiansen et al. 1988), may indicate a slightly older age (10,300–10,500 BP) for this boundary.

Pollen stratigraphy and vegetation history

The pollen stratigraphy is similar enough to that found in the Ålesund area that the assemblage zones defined by Kristiansen et al. (1988) are applicable to this area. The following description and discussion is based mainly on the diagram from Frøystadmyra II (Fig. 5).

Ål 1 Rumex/Oxyria *assemblage zone (12,600–12,000 BP)*

This zone is characterized by a high percentage of *Rumex/Oxyria* and a low percentage of *Betula*. The base of the zone was only identified in Dalevatn and it is assumed to be slightly younger than deglaciation which occurred around 12,600 BP.

A treeless arctic-alpine vegetation is suggested for this zone. *Rumex/Oxyria* was an important component of this vegetation, which together with the *Salix herbacea* leaves present in the sediments indicates the presence of extensive snow-beds in this region at this time. A certain degree of differentiation is evident from the changes in the composition of herbs above the marine/lacustrine boundary in Frøystadmyra II and III. The differentiation includes the initial development of a swamp vegetation around the lakes, as indicated by the presence of *Cyperaceae* and *Caltha* type (*Caltha palustris*). The sea shore was probably occupied by a light demanding vegetation which included several mountain herbs (e.g. *Chenopodium, Sedum, Asteraceae sect. Asteroidae*). High values of *Ranunculus* (*Anemone* type) at the level directly above isolation contact are attributed to an aquatic species, probably *Ranunculus peltatus*.

Ål 2 Betula-Empetrum *assemblage zone (12,000–11,000 BP)*

The lower boundary is defined by a distinct rise in the *Betula* curve at the same time as the values of *Rumex/Oxyria* decline. This boundary is dated to around 12,000 BP (Kristiansen et al. 1988) and we assume it is roughly contemporaneous within the entire Sunnmøre area. The *Betula* rise is probably due to the first occurrence of the tree form of *Betula* (*Betula pubescens*) at protected localities. However, a relatively low influx indicates that real birch forests did not occur during the Late Weichselian. A scanty heath vegetation is shown by the appearance of a low percentage of *Empetrum*.

The changes in the vegetation at the Ål 1/Ål 2 transition around 12,000 BP could possibly reflect a natural succession involving soil maturation and a closing in of the vegetation, independent of climate. However, after the preceding 600 year period, the changes seem to occur rapidly and simultaneously throughout the entire region, suggesting that climatic improvement instigated these changes. The appearance of *Filipendula* (most likely *Filipenduala ulmaria*) at this transition indicates a minimum mean July temperature of 8–9°C (Kolstrup 1979). By 11,500 BP the occurrence of *Myriophyllum* spp. and *Nymphaea* indicates a mean July temperature of not less than 10°C (Kolstrup 1979). The decline in the *Betula* curve at the top of the zone is below the lithostratigraphic boundary, the difference corresponding to some 50–100 years. This time lag is similar to that found by Larsen et al. (1984) whereas Kristiansen et al. (1988) found that only the influx of *Betula* pollen declined before the sediment changes at the lithostratigraphic boundary. A concurrent decline in the *Poacea* curve together with an increase in the percentages of *Salix* and *Rumex/Oxyria* might indicate a moister climate at the Allerød/Younger Dryas transition.

Ål 3 Salix-Artemisia *assemblage zone (11,000–10,200 BP)*

This zone is characterized by a low *Betula* curve, a high percentage of *Artemisia* and a high percentage of *Salix* in the lower part of the zone. The zone boundaries are close to the lithostratigraphic boundaries of the Leirstad Member. The relative importance of several herbs which are favoured by unstable soil increases, such as *Saxifraga oppositifolia* type, *Sedum* sp., *Cerastium* type, *Chenopodium,* and *Caryophyllaceae* indicates a reversion to open conditions. With the exception of *Artemisia* the influx of most pollen species decreases and the total reaches a minimum (89 pollen cm^{-2} yr^{-1}) at 492 cm (influx diagram is not presented). *Salix* was a dominant component of the vegetation around the lake during the early phase of the Younger Dryas. It is suggested that a substantial amount of snow accumulated in depressions and offered favourable habitats for the snowbed plant *Salix herbacea* and *S. polaris*. However, it is possible that part of the *Salix* pollen is derived from willow as suggested by Larsen et al. (1984).

The changes in the pollen composition associated with the *Salix-Artemisia* zone were caused by climatic deterioration in the Younger Dryas. The decline in the *Salix* curve, a relatively low influx of *Rumex/Oxyria* and the increasing importance of certain mountain herbs indicate a gradual transition to a drier, more continental type of climate.

Ål 4 Betula-Juniperus-Empetrum *assemblage zone*

The lower boundary coincides with the base of the Hatlen Formation (10,200–10,300 BP). Slightly above, there is a marked increase in *Empetrum* values and even further up a rise in *Juniperus* is noted. The arctic-alpine elements which were common in the previous zone disappear.

From 490 to 472 cm there is a dramatic increase (from 12 to 1100 pollen cm^{-2} yr^{-1}) in the influx of *Betula*, and this is most likely due to the establishment of *Betula pubescens*, as suggested by Kristiansen et al. (1988) for the Ålesund area. The influx of herb pollen was higher than during Ål 3. These changes in the pollen flora reflect the development of an open birch forest where the ground cover is dominated by grasses and ferns. In open, well-drained areas *Empetrum* heaths and later juniper bushes develop.

The investigated basins

Dalevatn, which is the only basin situated above the marine limit and contains only lacustrine sediments, is described first. The other basins used to construct the sea-level curve (Fig. 17) are described in the same order that they were isolated from the sea. These include Frøystadmyra III, Frøystadmyra II, Skolemyra, Litlevatnet followed by three basins, Frøystadmyra I, Kulturmyra and Almestadmyra, which were isolated at about the same time. With the exception of Almestadmyra, the lithostratigraphic units in all cored basins fit into a complete sequence where the highest have more lacustrine beds and the lower more marine beds (Fig. 2).

For each basin an 'assumed age' is given for the isolation of the lake. These proposed ages are

FRØYSTADMYRA II

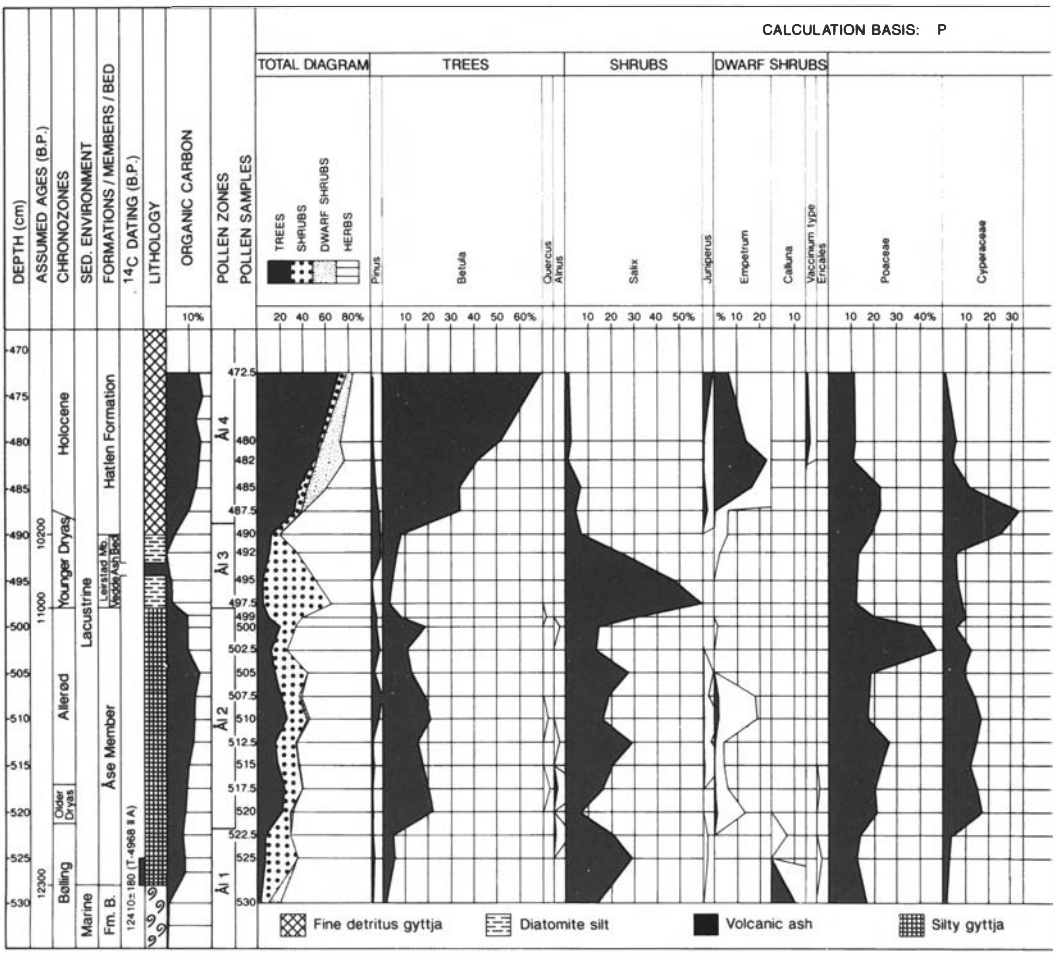


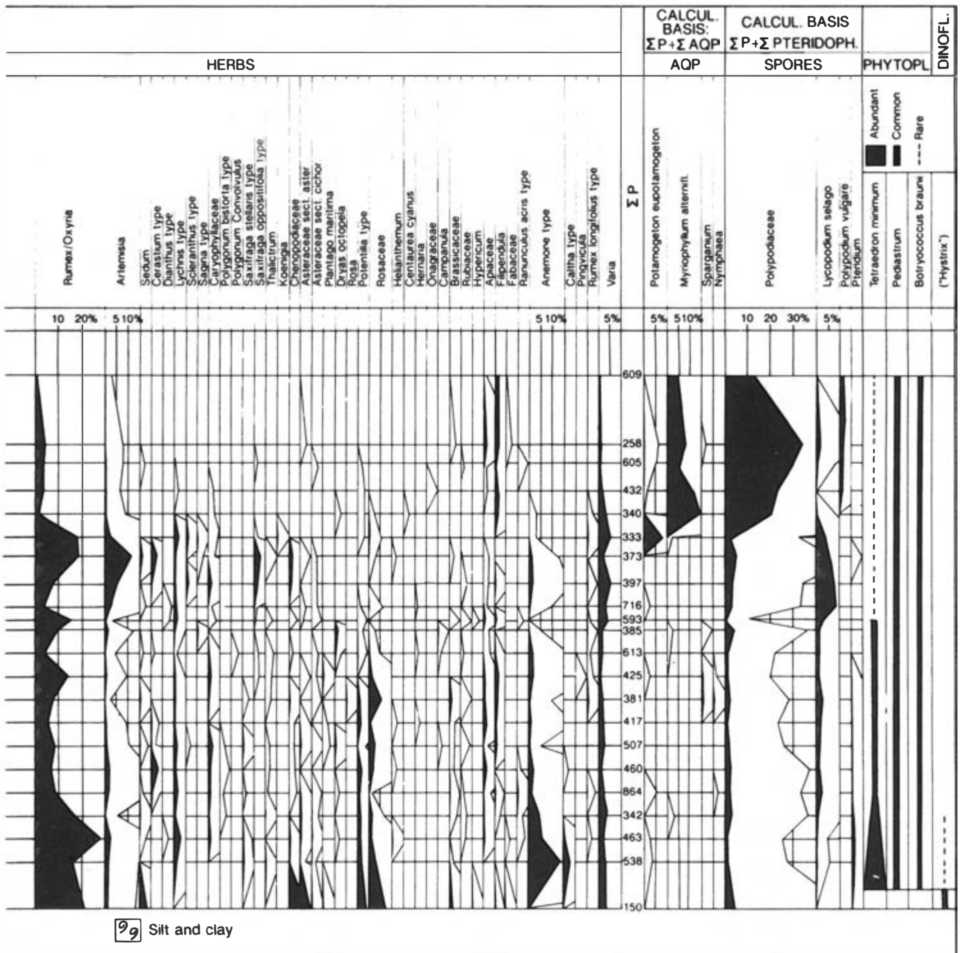
Fig. 5. Pollen diagram from Frøystadmyra II.

based on critical assessments of the individual radiocarbon dates together with a correlation to regional litho- and biostratigraphy (see Fig. 6 in Svendsen & Mangerud 1987).

Dalevatn (UTM coordinates 228011), 30.5 m a.s.l.

The lake is situated in a valley at the southern end of Gurskøy (Fig. 1) and it is surrounded by bog from which the samples were taken. The outlet is a rock threshold 30.5 m a.s.l. which has recently been lowered by 1–2 m. In this basin the entire sequence is most likely of lacustrine origin (Fig. 2). The lower unit is massive silt of the Mehuken Member.

The pollen diagram (Fig. 6) shows a noticeable decrease in the *Rumex*/*Oxyria* curve between 668 and 658 cm at the same time that the percentage of *Betula* increases from below 10% to above 20%. This transition represents the boundary between the *Rumex*/*Oxyria* and *Betula-Empetrum* assemblage zones. Provided there is a constant sedimentation rate throughout the Åse Member this suggests that the lower boundary of this unit is around 12,500–12,600 BP. No radiocarbon dates are available from this basin.



Frøystadmyra III (UTM coordinates 291147), 23 m a.s.l.

The almost circular basin is about 50 m in diameter and the catchment area is only about four times the basin area (Figs. 7, 8). The present outlet is across a moraine threshold (22.2 m a.s.l.) which seems to have been lowered by 1–2 m during recent cultivation of the area. The original threshold has been estimated to be 23 m a.s.l.

In this basin Formation A is directly overlain by the lacustrine Åse Member (Fig. 2). Very few diatoms were found below the assumed isolation contact, but frequent dinoflagellate cysts (Fig. 5) confirm that the sediment is of marine origin. In addition, the high trophic status as evident by the flourishing of freshwater algae (*Tetrahedron minimum* and *Pediastrum*) at the base of the Åse Member is assumed to be an effect of the isolation of the basin.

The fact that Formation A is directly overlain by the Åse Member indicates that the lake emerged shortly after deglaciation and before the commencement of sedimentation of the marine formation B. Provided a constant sedimentation rate for the Åse Member the transition level from the *Rumex/Oxyria* to the *Betula-Empetrum* assemblage zone suggests that the marine/lacus-

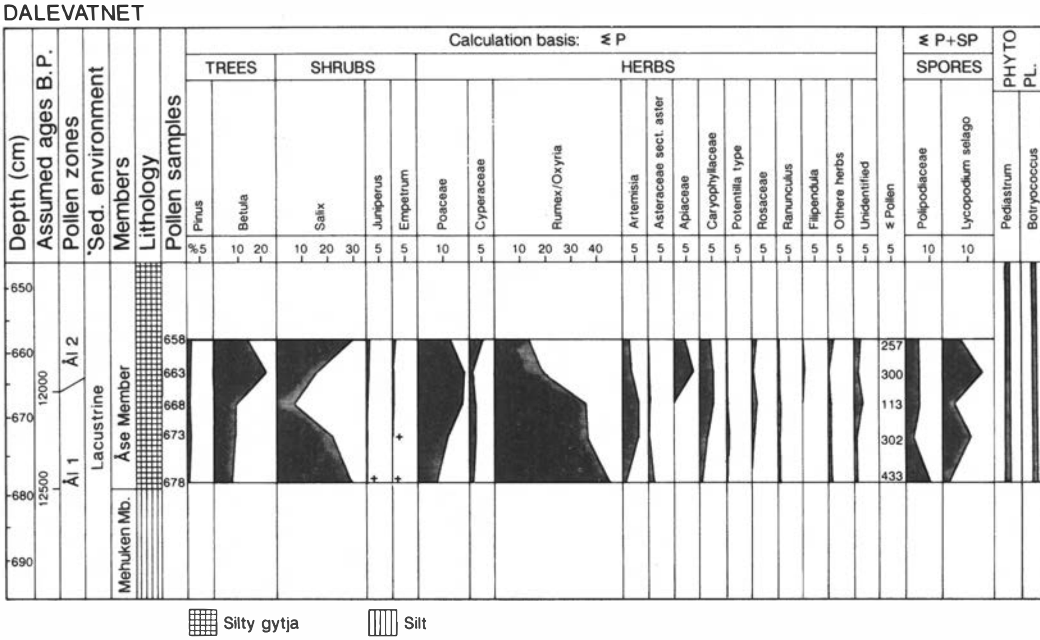


Fig. 6. Pollen diagram from Dalevatn.

trine boundary is between 12,400 and 12,550 BP. A gyttja sample (766-770 cm) from the level directly above the isolation contact was radiocarbon-dated to 12,220 ± 370 BP (T-5146 A). The assumed age of isolation is 12,500 BP.

Frøystadmyra II (UTM coordinates 300157), 18 m a.s.l.

The bog is situated 1000 m to the NE of Frøystadmyra III (Fig. 7). The basin is about 100 × 100 m and at present is drained by a ditch which cuts through a till threshold at the western end of the bog. A considerable part of the surrounding area is now cultivated. There are no brooks entering the lake and the main supply of water is by means of surface runoff.

Frøystadmyra II has a thicker (1 m) marine sequence than Frøystadmyra III and includes Formation B. The isolation contact coincides with the lithological transition from Formation B to the Åse Member (Figs. 2, 5). Three samples were analysed for diatoms across this boundary between 530 and 525 cm. The brackish sediments represent a narrow zone (less than 3 cm), indicating that the basin was isolated during a rapid regression. The pollen stratigraphy shows that the isolation contact occurs well below the transition from the *Rumex/Oxyria* to the *Betula* assemblage zones (Fig. 5). Lacustrine gyttja (524–527 cm) from directly above the isolation contact was radiocarbon-dated to 12,410 ± 180 BP (T-4968, IIA). The assumed age of isolation is 12,300 BP.

Skolemyra (UTM 262 162), 12.4 m a.s.l.

Part of the basin (Fig. 10) was not available for coring as it was filled in for the construction of a school building. There are no brooks which drain into the basin and the outlet is a bedrock threshold at the southern end of the bog.

Generally the lithostratigraphy in this basin is similar to that in Frøystadmyra II (Fig. 2). However, after 1 m of marine sediments a more substantial brackish period is shown by well-defined red brown and green lamina (565–562 cm) directly below the marine/lacustrine boundary (Fig. 3). Only three samples (563, 560 and 555 cm) were analysed for pollen, showing that the marine/lacustrine boundary lies within the *Rumex/Oxyria* zone (Fig. 11). This age is confirmed by a radiocarbon date directly above the isolation contact (12,090 ± 200 BP, T-5147 A). The assumed age of isolation is 12,250 BP.

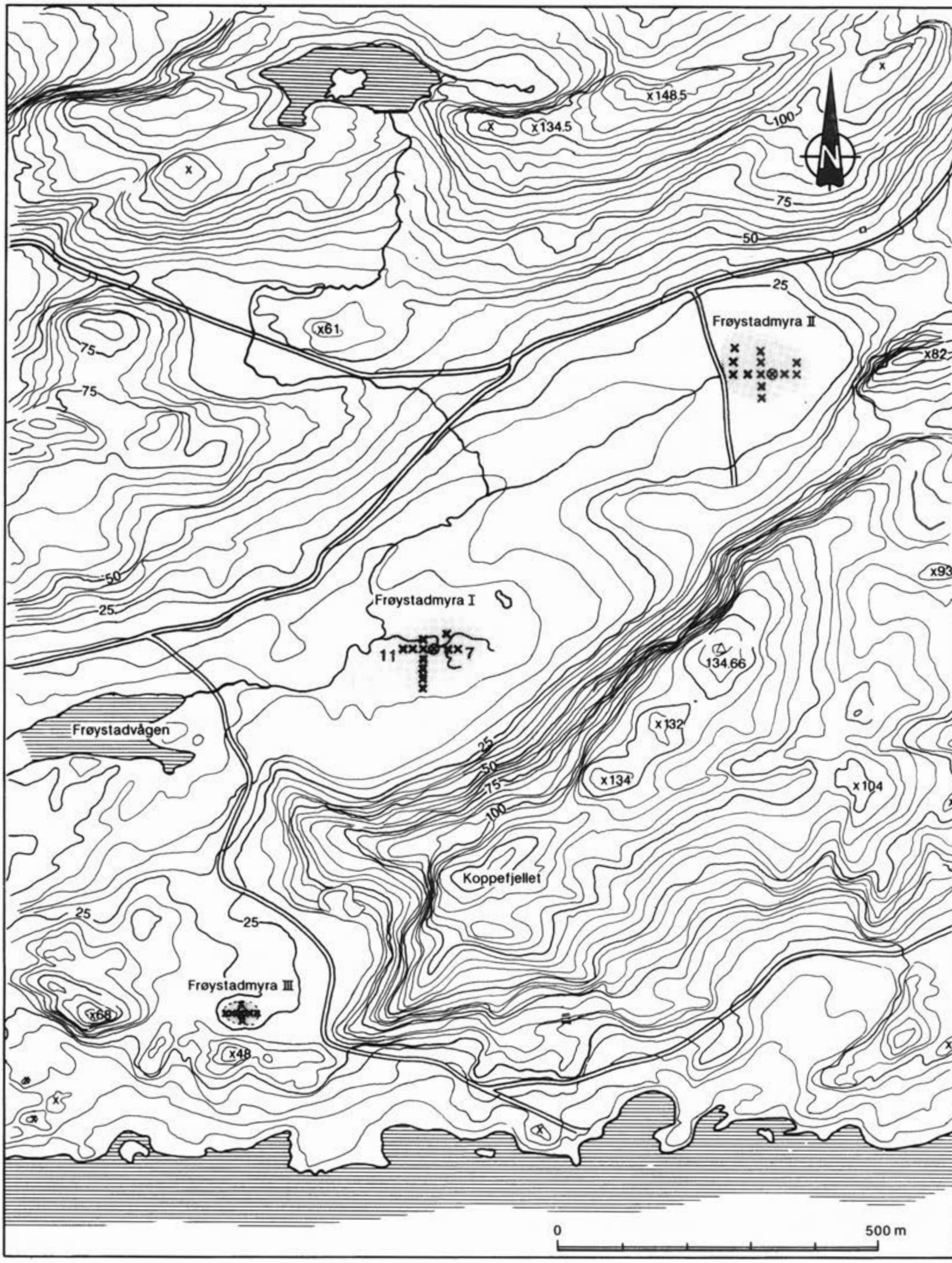


Fig. 7. A map of the bogs Frøystadmyra I, II and III, Leinøy (Fig. 1). The basins are shaded and the crosses mark coring points. The location of the analysed core is encircled.

Fig. 8. Photograph of Frøystadmyra III viewed towards the west. The bog is encircled by trees.

In the lacustrine sequence there is a layer of dark brown, coarse gyttja containing sediment lumps of the Åse Member, terrestrial turf, stones and gravel which rests on the Vedde Ash Bed (Fig. 2). This mixture of sediments must be the result of an early Holocene slumping. The sediment above consist of a dark brown, fine detritus gyttja of the Hatlen Formation.

Litlevatn (UTM coordinates 349096), 19.2 m a.s.l.

Litlevatn is a long and narrow lake basin between low rock outcrops (Fig. 1). Most of the basin is filled with lacustrine sediments and a layer of peat on the top. The outlet is a bedrock threshold in the northeastern end of the basin.

Unlike the preceding basins, which contain a relatively thin marine sequence, this basin has a long marine sequence (915–722.5 cm) that is overlain by a relatively thin layer of the Åse Member (722.5–708.5 cm) (Fig. 2). Distinct brown, red and green lamina occurring in the upper part of Formation B between 727 and 722.5 cm suggests a brackish transition period of some duration. The pollen diagram shows that the isolation contact is younger than the ***Rumex/ Oxyria*** assemblage zone and well into the Allerød (Fig. 12). A sample of lacustrine gyttja (723–719 cm) from directly above the isolation contact was radiocarbon dated to 11,510 ± 120 BP (T-5148 A). The assumed age of isolation is 11,500 BP.

Frøystadmyra I (UTM coordinates 295153), 6.2 m a.s.l.

The bog is situated about 500 m to the southwest of Frøystadmyra II (Fig. 7). The basin is about 250 m long and 100 m wide with a bedrock threshold in the western end. In the lower part there is 3.3 m of marine and brackish sediments (Fig. 2). Because of a late isolation the basin does not contain sediments of the Langevåg Formation. The lithostratigraphic profiles show that the upper boundary of Formation B is an erosional surface which implies that the primary isolation contact is missing in this basin (Fig. 13). Seven

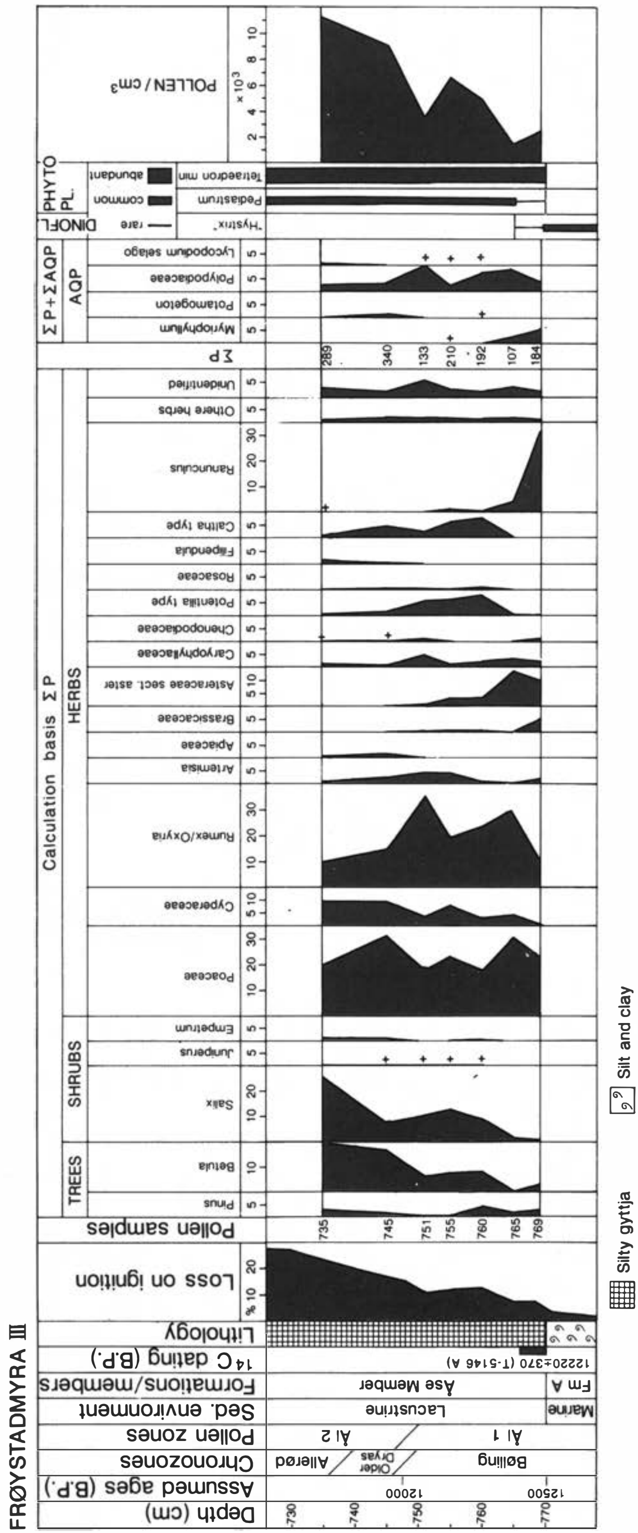


Fig. 9. Pollen diagram from Frøystadmyra III.

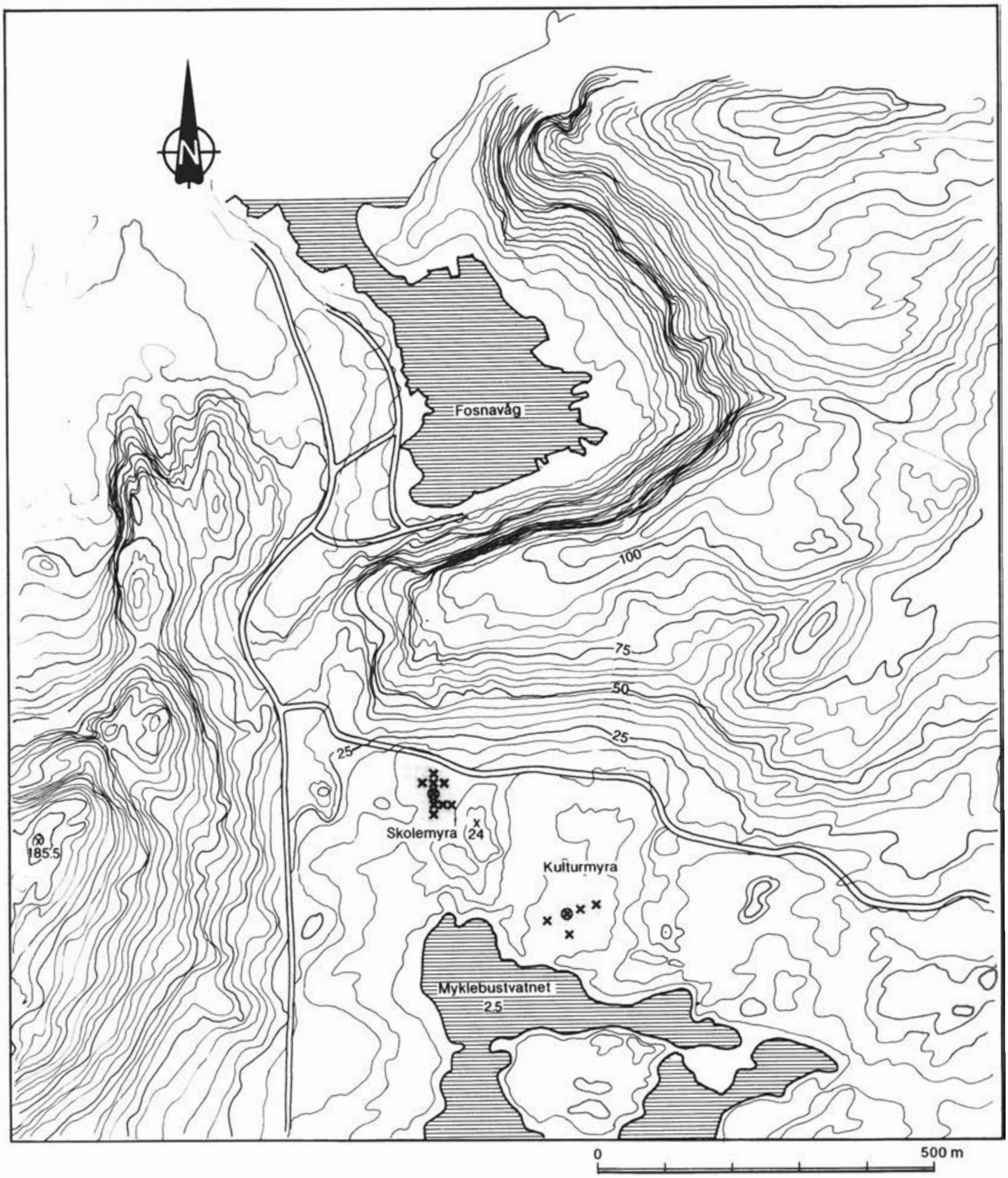


Fig. 10. Map of the bogs Skolemyra and Kulturmyra, Bergsøy (Fig. 1). The basins are shaded and the crosses mark coring points. The location of the analysed core is encircled.

samples were analysed for diatoms between 494.5 and 540 cm in core 9 (Svendsen 1985) (Fig. 13). These indicate that the upper part of the formation (from 540 cm and upwards) was deposited in a brackish environment. The occurrence of well-defined green and brown lamina between 533.5 and 513 cm (Fig. 14) supports the interpretation of a long-term brackish environment. The appearance of lamination suggests a reducing benthic environment with the absence of burrowing organisms. This might have resulted from the sea leval falling below a certain threshold.

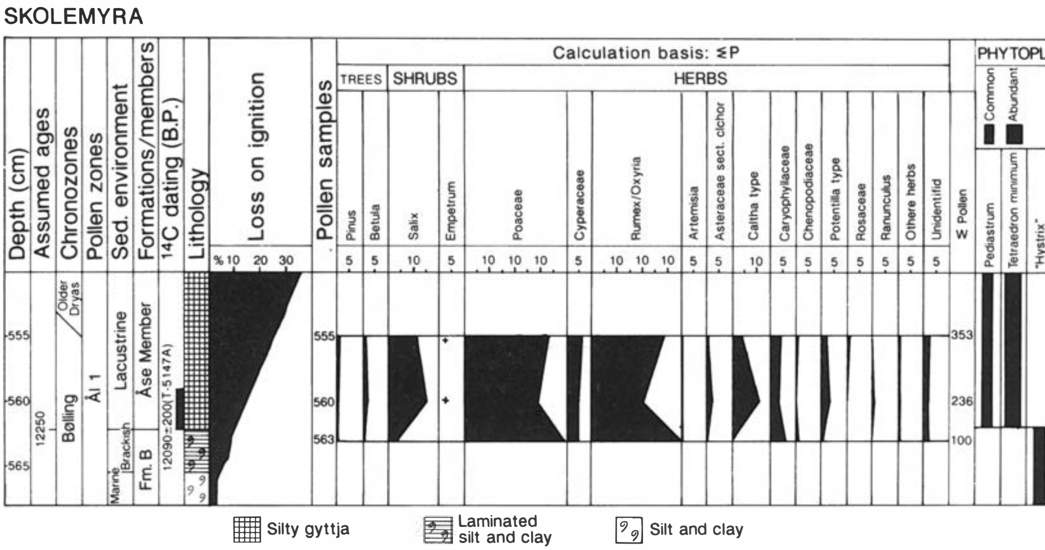


Fig. 11. Pollen diagram from Skolemyra.

The reappearance of massive sediments above the laminated zone might represent a minor transgression which was not significant enough to affect the diatom composition in the basin.

Radiocarbon dates from the base of the laminated sequence (530–533 cm) and from the top of the formation (496.5–493.5 cm) were 10,980 ± 160 (T-4969 A) and 10,510 ± 190 BP (T-4966 A) respectively (Fig. 14, Table 1). Both dates agree with the expected age as suggested from the pollen and lithostratigraphy. A decrease in the percentage of *Betula* along with a distinct increase in the values for *Artemisia*, *Salix* and *Oxyria/Rumex* indicate that the Allerød/Younger Dryas transition occurs between 540 and 530 cm (Fig. 14). An age of around 10,300 BP is suggested for the upper boundary of the marine formation (B) by assuming a constant sedimentation rate for the sequence above the Vedde Ash Bed.

Above Formation B is an erosional unconformity (Figs. 13, 14) covered by a layer of sorted sand with diatoms of a marine/brackish origin. Waves and/or strong currents associated with the Tapes transgression are the most plausible mechanisms for this severe erosion and subsequent deposition of coarse sand. Above the sand is a coarse gyttja layer consisting primarily of redeposited organic macro debris, mostly mosses (*Sphagnum*). The terrestrial origin of these plant remnants indicates that the sediment was washed into the basin from the surrounding lake shore. Above this coarse organic layer is a thin silty layer followed by gyttja of the Hatlen Formation. The pollen of water plants shows that the sequence above the sand layer was deposited in a lake (Fig. 14).

The lacustrine sediments have a completely different pollen flora compared to the brackish/marine sediments below (Fig. 14). In the lacustrine sequence the occurrence of *Corylus* indicates that the sediments post-date the *Corylus* rise around 8300 BP (Kristiansen et al. 1988). The occurrence of 5% *Alnus* at 492 cm indicates the tentative presence of alder. In the Bergen area to the south the colonization of alder has been dated to 7600–7800 BP (Kaland et al. 1984). The coarse organic layer was radiocarbon to 8480 ± 160 BP (T-4967 A) and the base of the undisturbed lacustrine gyttja was dated to 8140 ± 110 BP (T-8185). The pollen data discussed above suggest that these dates are too old; this problem is discussed in more detail later. Regardless, the dates reveal that there is a hiatus of at least 2000 years between the top of the marine and the base of the lacustrine sediments.

Kulturmyra (UTM coordinates 262162), 2.5 m a.s.l.

The bog is about 100 × 70 m and is a sub-basin of Lake Myklebustvatnet (Fig. 10). It is separated

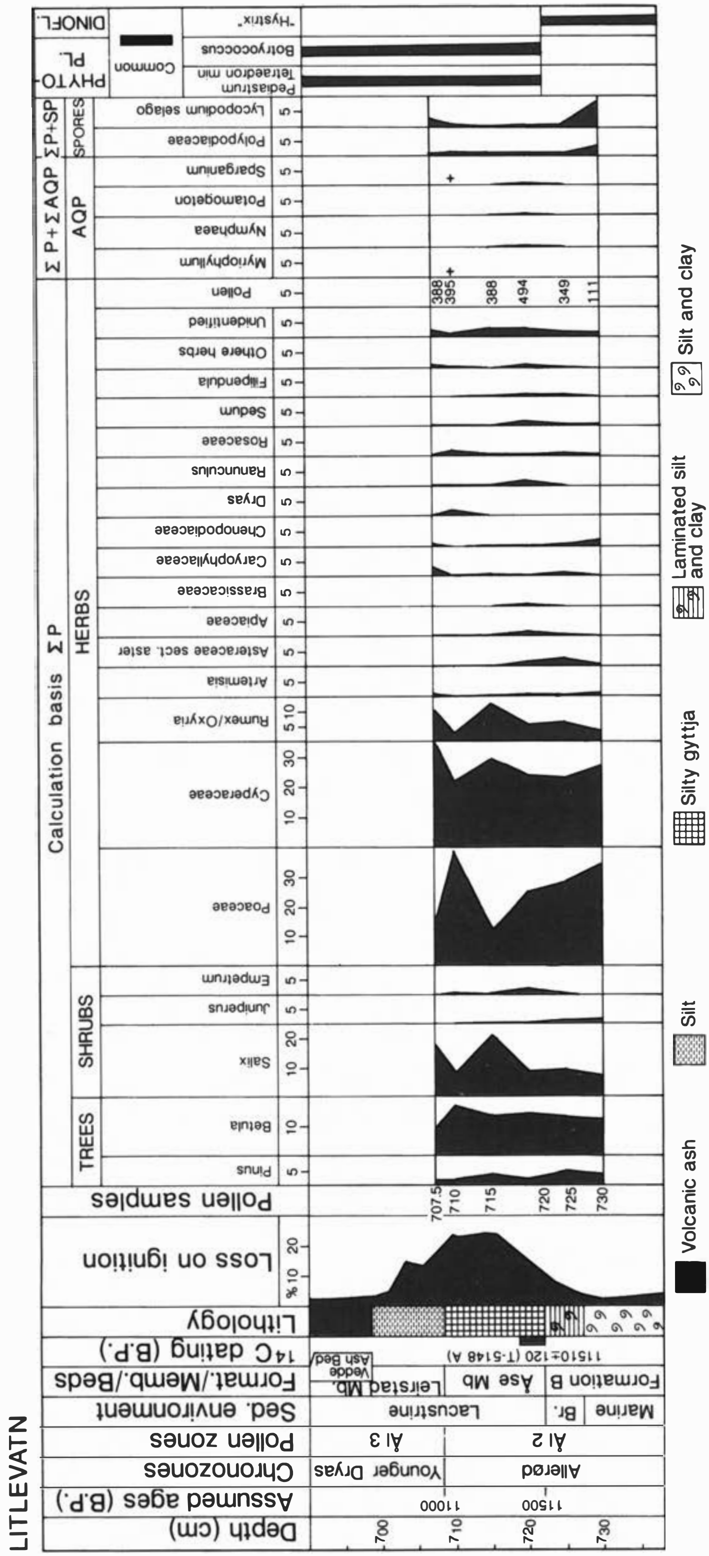


Fig. 12. Pollen diagram from Litlevatn.

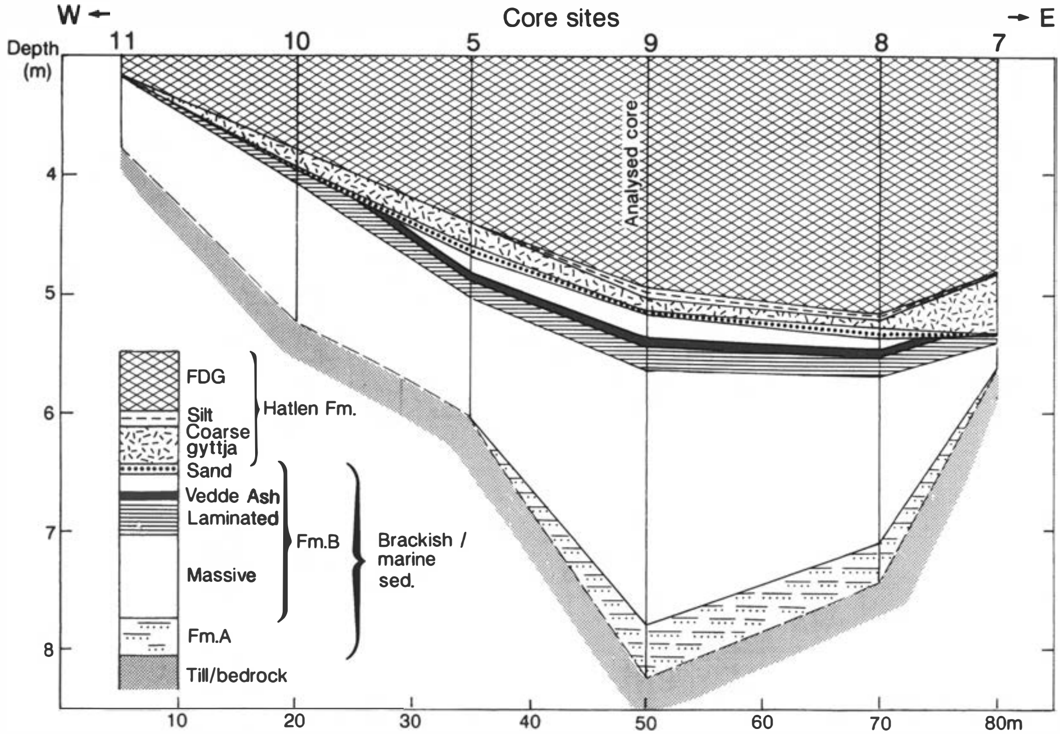


Fig. 13. Lithostratigraphic profile (W–E) across Frøystadmyra I. The coring sites are shown in Fig. 7. Note the angular unconformity beneath the sand bed.

from the lake by a bedrock threshold that is about the same level as the lake. As in Frøystadmyra I the lacustrine Hatlen Formation directly overlies a long marine sequence consisting of Formations A and B (Fig. 2). Seven samples between 640 and 577 cm were analysed for diatoms (Svendsen 1985) which indicate a long period of brackish water prior to the isolation of the basin. The presence of the Vedde Ash Bed between 612.5 and 612 cm shows that the transition from a marine to a brackish environment occurred prior to 10,600 BP. The pollen analysis shows that the isolation contact is contemporaneous or slightly younger than the start of the *Betula* rise at 10,200–10,300 BP (Fig. 15). A sample of lacustrine gyttja (566–563 cm) directly above the isolation contact was radiocarbon-dated to 10,500 ± 140 BP (T-5145 A), which seems slightly too old. We assume the age of isolation is 10,200 BP, in accordance with the pollen correlation.

The Tapes transgression is evident from another marine sequence higher up in the core (Fig. 2).

Almestadmyra (UTM coordinates 269025), 13.7 m a.s.l.

The bog (Fig. 1) is situated in a valley that extends from the head of the Gurskenfjorden. The exact dimension of the basin was not determined, but it is approximately 200 × 200 m. The bog has a moraine threshold at the western end.

The lithostratigraphy (Fig. 16) was described in the field based on only a few samples taken with a Russian peat sampler and the lateral distribution of the layers is poorly known. The lithostratigraphy is to some degree different from the other basins and it was not possible to correlate all of the beds with the stratigraphic units in other basins.

Formation B (820–771 cm) is a dark grey gyttja silt which is stained by monosulphides. Small fragments of *Mytilus edulis* and/or *Modiolus modiolus* were found from the base and up to 790 cm. Few diatoms were found in the upper part of Formation B, but the composition suggests a brackish/marine origin. Formation C is a gyttja

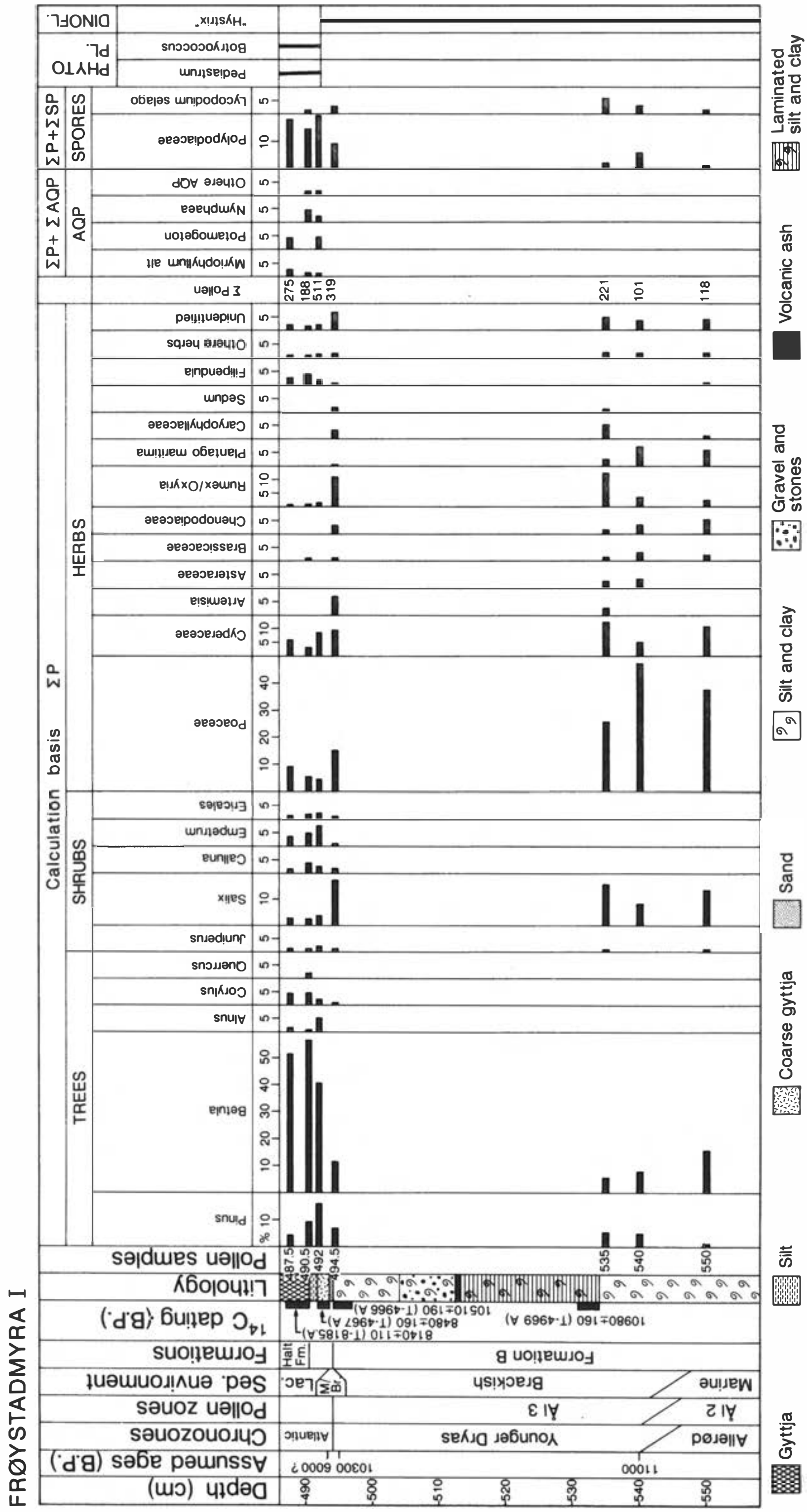


Fig. 14. Pollen diagram from Frøystadmyra I.

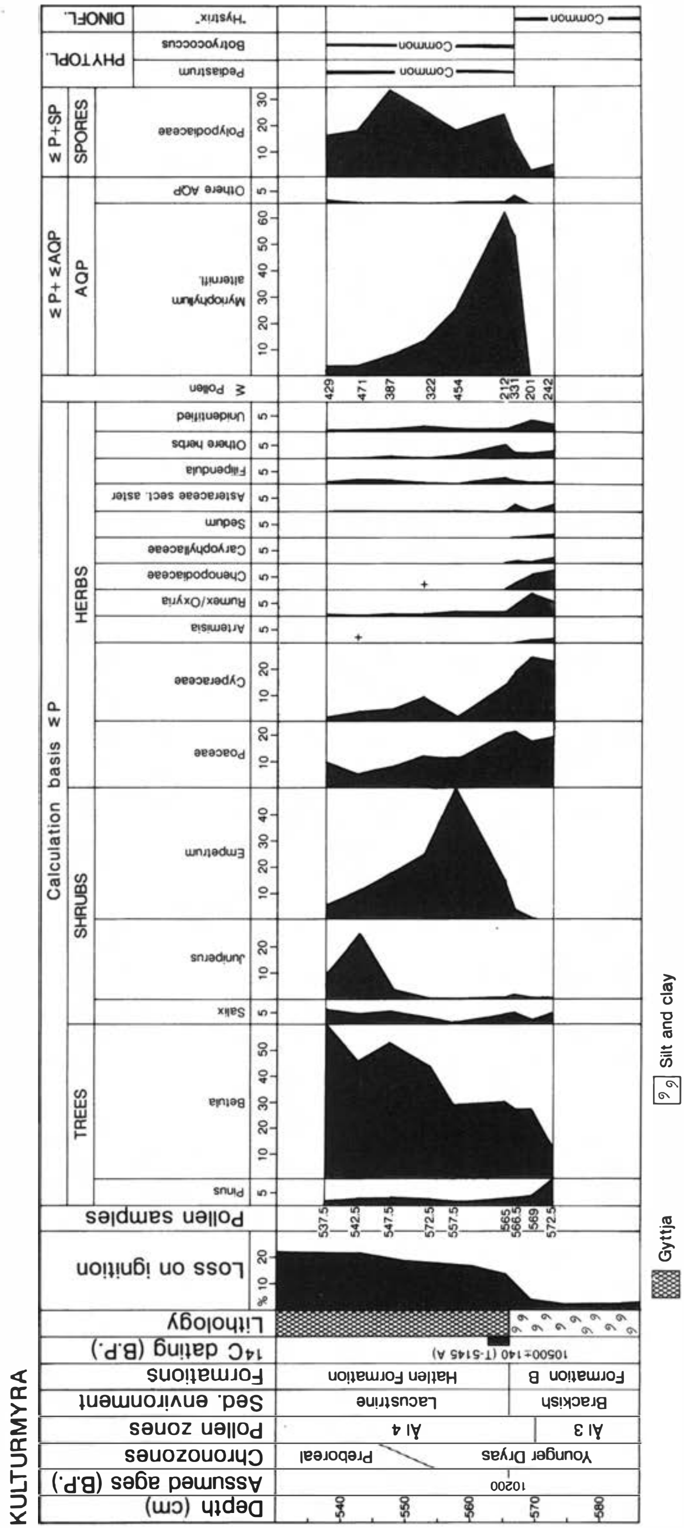


Fig. 15. Pollen diagram from Kulturmyra.

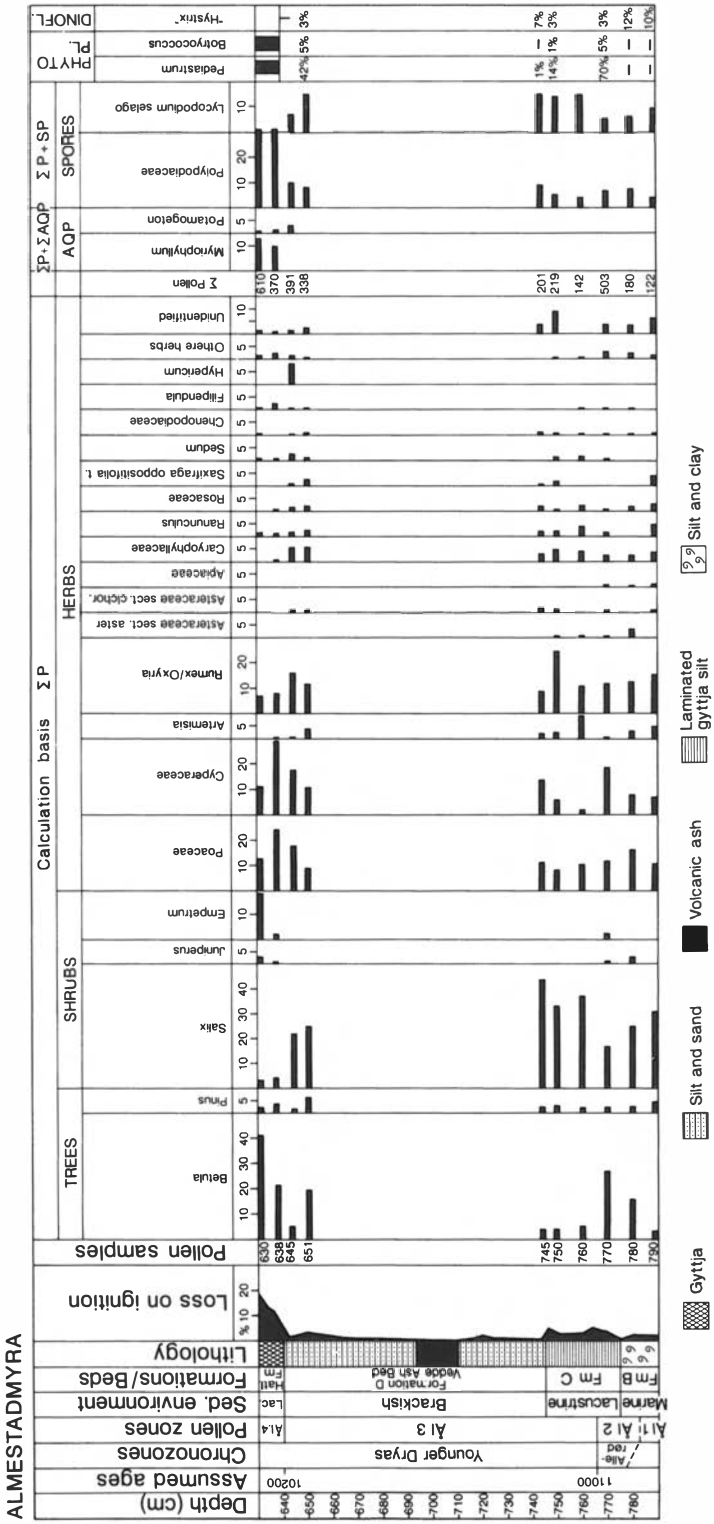


Fig. 16. Pollen diagram from Almestadmyra.

silt characterized by distinct black and brown lamina. The lower boundary is sharp whereas the upper boundary is more gradual. The presence of diatoms as well as the occurrence of green algae (*Pediastrum, Botryococcus*) indicate a lacustrine environment. However, a few (3%) *Dinophyceae* cysts ('Hystrix') were also found, which may indicate that the lake environment was a little influenced by intrusion of sea water. The pollen stratigraphy (Fig. 16) shows that this unit was deposited during the late Allerød and early Younger Dyras. Formation D (746–640 cm) is a mixture of grey silt and sand with a very low content of organic material. The Vedde Ash Bed (710–693 cm) occurs in the middle of this formation. A mixed diatom flora reflecting a brackish environment was found at 746, 710, 664 and 646 cm, whereas only lacustrine taxa were found at 725 cm. Formation D is overlain by the lacustrine Hatlen Formation. There are no radiocarbon dates available from this sequence, but the pollen stratigraphy shows that the isolation contact coincides with the *Betula* rise at around 10,200 BP.

Some 35 cm up in the Hatlen Formation there is a distinct sequence consisting of a well-defined layer of sorted sand (608–606 cm), a grey-brown silty gyttja (606–603 cm) and brownish-grey gyttja silt (603–601 cm). The diatoms are a mixture of lacustrine and brackish flora. The origin of this sequence is uncertain; however, it is not likely that the basin was transgressed during the Holocene because the elevation of the threshold is more than 4 m above the Tapes level. The possibility that a tsunami caused this sequence is discussed below.

Sea level history

Isobases

Isobases are contours connecting sites of equal emergence and define the strike direction for the corresponding tilted shorelines. In this area the Younger Dryas shoreline was defined by the threshold elevations of Frøystadmyra I, Kulturmyra and Almestadmyra (Fig. 1), which were isolated simultaneously around 10,200 BP. A precise correlation of these basins was possible because in each of them the Vedde Ash Bed occurs in the brackish sediments and the marine/lacustrine boundary corresponds to the *Betula* rise. Because Kulturmyra and Frøystadmyra I are situated too close to each other for a precise determination of the isobase direction, the Younger Dryas levels in these three basins were compared to those in the Ålesund area (Lie et al. 1983). The direction of the isobase between Sula and Leinøy was found to be N35°E with a shoreline gradient of ca. 1.3 m/km. This agrees with results based on morphological criteria (Sollid & Kjenstad 1980; Reite 1968). Reite (1968) and Undås (1942) assumed that the Younger Dryas and the Tapes transgression shorelines have a similar isobase direction. This has been confirmed by Svendsen & Mangerud (1987).

A sea-level curve for Leinøy

A relative sea-level curve (Fig. 17) has been constructed for Frøystadvågen, Leinøy (Figs. 1, 7). In order to use all basins to construct the age-elevation diagram, the elevations of the thresholds for Skolemyra, Kulturmyra and Litlevatn are corrected for differential uplift relative to Frøystadmyra I, II and III. The well-documented Younger Dryas shoreline gradient of 1.3 m/km (Svendsen & Mangerud 1987) was used for all basins. Thus, the threshold of Litlevatn (19.2 m a.s.l.), which is situated 7.5 km to the east of the reference isobase (Fig. 1), is corrected by 10 m when used for construction of this curve (Fig. 17). Any divergence from this gradient for Litlevatn is considered insignificant (less than 1 m), as the lake was isolated from the sea only a few hundred years before the Younger Dryas.

The curve (Fig. 17) is drawn visually as a regression line between the dated threshold elevations for each basin. These levels represent the former high tide. The present tidal range is about 2–3 m and the mean sea level is estimated to be at about 1–1.5 m below the curve.

The marine limit and the age of deglaciation

From the basins studied the marine limit on Leinøy could not be determined exactly because the highest basin studied (Frøystadmyra III, 23 m a.s.l.) is situated below the marine limit. Assuming that Leinøy was deglaciated at the same time as Gurskøy then the marine limit can be bracketed between 23 and 28 m a.s.l. based on the data from Dalevatn from Gurskøy. This figure is also supported by field observations of the

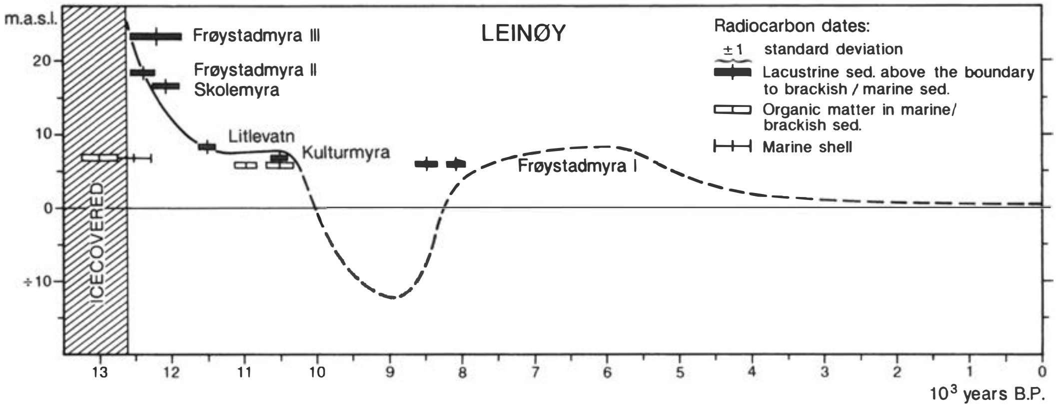


Fig. 17. Sea-level curve for Leinøy. The Holocene part is deduced from a shoreline diagram constructed by Svendsen & Mangerud (1987).

maximum elevation of beach sediments on Leinøy. The marine limit was most likely formed immediately after the deglaciation. Both the basal radiocarbon dates from the marine sediments in Kulturmyra and the oldest dates of lacustrine gyttja which were used to construct the sea-level curve (Fig. 17) suggest an age of around 12,600 BP for this event. This is in accordance with dates from the Ålesund area, which lies farther inland, and where a slightly younger age (12,300–12,500 BP) for the deglaciation has been suggested (Kristiansen et al. 1988).

Sea-level changes during the Late Weichselian

The curve shows a rapid emergence (more than 3 m/100 year) following deglaciation at approximately 12,600 BP. From the late Allerød and during the Younger Dryas a prolonged standstill is demonstrated. This standstill is evident as a brackish zone in Frøystadmyra I and Kulturmyra which must have lasted for several hundred years. The rapid Holocene emergence is contemporaneous to the *Betula* rise and the deposition of the Hatlen Formation, for which a minimum age of 10,200 BP was used. If a slightly older age (10,300–10,500 BP) is used the levelling out of the sea level curve in the Younger Dryas becomes shorter.

The stratigraphy recorded in Almestadmyra indicates that the sea-level history is slightly different in the area farther south. The late Allerød and early Younger Dryas sea levels were apparently below the 10,600 BP shoreline, which means that a small transgression occurred around 10,600 BP. If the Allerød and Younger Dryas isobases are not exactly parallel in this southern area (Svendsen & Mangerud 1987) then this could explain the transgression. This might indicate that the Younger Dryas transgression which is described further south (Anundsen 1985) begins near this latitude. Regardless, the final rapid emergence is assumed to have occurred around 10,200 BP, as predicted by the curve.

Sea-level changes during the Holocene

The Holocene part of the sea-level curve is deduced from a shoreline diagram (Svendsen & Mangerud 1987) and is not based on observations from this particular area. The diagram predicts that the Tapes transgression on Leinøy culminated at 8 m a.s.l. around 6000 BP, which means that Frøystadmyra I (6.2 m a.s.l.) would have been transgressed. This is supported by the presence of beach ridges associated with the Tapes transgression maximum around 10 m a.s.l. However, the radiocarbon dates from Frøystadmyra I (T-4976 A and T-8185 A) do not agree with the deduced Holocene sea-level curve.

As described above, an unconformity in Frøystadmyra I (Fig. 13) shows that the early Holocene sediments were removed by erosion, and it seems likely that this hiatus and the sand layer were caused by the Tapes transgression. Corings in the Ålesund area have shown that in most basins the Tapes transgression eroded all of the soft early Holocene lacustrine gyttja.

When the diagram was constructed, Svendsen

& Mangerud (1987) disregarded the date from the mixed sediments above the sand layer (8480 ± 160, T-4967 A) because it was from a bed including redeposited material. Later, a sample from the base of the overlying, apparently undisturbed, gyttja was submitted for dating. These lacustrine sediments must have been deposited after the culmination of the transgression which caused the erosion. The obtained age (8140 ± 110, T-8185 A) is consistent with the former date. However, both dates are incompatible with the shoreline diagram in that they are 2000–3000 years older than the predicted transgression maximum (Fig. 17).

As discussed by Svendsen & Mangerud (1987) an age around 6000–7000 BP for the culmination of the Tapes transgression on Leinøy is supported by several radiocarbon dates from the outermost coast of Sunnmøre (Bjerck 1982; Indrelid 1975; Hafsten & Tallantire 1978; Longva et al. 1983). In addition, this age has recently been confirmed by three archaeological dates obtained from a beach ridge (ca. 10 m a.s.l.), which is correlative with the Tapes transgression maximum on the island of Valderøya (Randers & Höglin 1988), situated some 25 km to the northwest of Leinøya. Even though it is quite possible that the Tapes transgression in this area culminated somewhat earlier than indicated on this deduced curve (ca. 6000 BP), an age as old as 8000–8500 BP, as suggested by the two mentioned dates, conflicts with nearly all dates of the Tapes transgression from western Norway (Kaland 1984; Aksnes 1986; Svendsen & Mangerud 1987). The validity of the two dates from Frøystadmyra I should therefore be critically re-examined.

Possible indications of a tsunami

In Scotland the occurrence of sand layers interbedded in terrestrial peat in a number of localities has been interpreted as a result of a tsunami (gigantic sea wave) dated to around 7000 BP (Dawson et al. 1988; Long et al. 1989). They ascribe this tsunami to large submarine slides from the continental slope along the western coast of Norway (Jansen et al. 1987). If these slides caused tsunamis of such a magnitude, then the coast of western Norway must have been affected, even though the direction of the slide was from the coast. Along the outermost coast such deposits could have been removed by the Tapes transgression, that culminated at a later date (Fig. 17) or they can be confused with sediments deposited as a result of the transgression. Further inland (e.g. the Ålesund area) the transgression maximum would pre-date tsunamis around 7000 BP, and thus possible tsunami sediments should be more easy to detect.

In Almestadmyra (13.7 m a.s.l.) we have described a sand layer interbedded in the lower part of the Holocene lacustrine gyttja. The presence of brackish diatoms indicates some marine influence. According to the shoreline diagram (Svendsen & Mangerud 1987) The threshold of this basin is 4 m above the Tapes transgression maximum and this rules out the possibility that the sand was deposited as a result of a marine transgression. Even though this sand layer has not been dated or studied in detail, we propose that it may represent a tsunami deposit.

In Skolemyra (12.4 m a.s.l.), which is situated around 5 m above the Tapes level and 6 m above the 7000 BP level (Fig. 17), a disturbed layer which includes terrestrial turf is resting discordantly on the Vedde Ash Bed (Fig. 2). This layer occurs in the deepest part of the lake and is apparently the result of slumping. Because the surrounding topography is relatively flat and not conducive to slumping an external cause such as a tsunami is a plausible trigger for this slumping event in this basin.

Conclusions

The Late Weichselian sea-level curve for Leinøy depicts a similar course of shoreline displacement as the other two curves from the Ålesund area, Sula (Lie et al. 1983) and Stette (Svendsen & Mangerud 1987). Following deglaciation, all three curves show a rapid emergence followed by a levelling out during the Younger Dryas. However, there are two minor differences. The emergence on Leinøy was slightly slower, and during the Younger Dryas there was a stillstand on Leinøy whereas in the Ålesund area there was a slight regression. These differences can be explained by the tilted shorelines and the increasing intensity of the uplift towards the interior (Svendsen & Mangerud 1987).

As demonstrated by Svendsen & Mangerud (1987) the shoreline geometry which accommodates these curves suggests a slowdown of the uplift rate during the Younger Dryas, most likely due to a halt in the retreat of the ice sheet. The stillstand on Leinøy shows that the isostatic and eustatic changes balance each other for nearly a thousand-year period. This indicates that the eustatic rise during this interval was even and smooth with no rapid high amplitude changes. This curve is situated 80 km west of the Younger Dryas ice sheet and the total glacio-isostatic uplift during this period is considered to be small, suggesting that the total eustatic rise was also small, most likely less than 10 m. By the way of comparison the transgression from 9000 to 8000 BP required more than 20 m of sea level rise. This suggests a marked increase in the rate of the eustatic rise during the early Holocene.

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