Thickness and layering of the Odbergmoen Late Weichselian and Holocene sediments in Lågendalen, southeastern Norway

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The Odbergmoen area in lower Numedalen (Lågendalen) is an overdeepened glacial basin with approximately 200 m of Weichselian and Holocene sediments. The area was deglaciated approximately 10,500 yrs B.P. with a Marine Limit of 175 m a.s.l. Seismic refraction, vertical electrical sounding, and gravity studies indicate the following stratigraphy: 60–110 m high-velocity sediments (till) are found below 60 m Late Weichselian and Holocene clays. 30 m of fluvial/estuary sand cover the clay in the central part of the basin. When the area rose above sea-level (7000 B.P.), nearly $300 \cdot 10^6 m^3$ of sediments had been deposited above the till. During the following 4000 years, the river eroded a 30 m deep channel, and approximately $63 \cdot 10^6 m^3$ sand, silt, and clay were transported southwards in the valley/fjord area.

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At the end of the Ra-period (Early Younger Dryas Chronozone, cf. Mangerud et al. 1974), the ice front retreated rapidly from Larvik to Kongsberg, and a long and narrow fjord, 'Numedalsfjorden', was formed between Kvelde and Kongsberg (Fig. 1B).

The Odberg area is located in the outer part of this glacial fjord. Average recession rates of the ice front were around 100 m per year, but several lateral and frontal deposits indicate a stepwise retreat of the glacier front up the valley from Larvik to Kongsberg (Jørgensen and Sørensen 1979). This stepwise retreat was to a large extent induced by the occurrence of overdeepened basins which became calving bays. A reconstruction of the terminal position of the glacier in the study area (Fig. 2) is modified from Hassum (1967).

The Odbergmoen was mapped in scale 1:5000 in connection with the Numedal Project (Rosenqvist 1969). Fig. 1 shows the distribution of different late glacial and Holocene sediments in the area. After mapping the following questions were unanswered: How deep was the basin, and what were the thickness and volume of different sediments that were deposited in the basin during and after the ice retreat? We have tried to answer these using a combination of different geophysical methods.

Geophysical data

Seismic refraction

A 630 m long refraction seismic profile was shot along the river bank in the middle of the basin (Figs. 1 and 3). The geophones were placed below the water table to assure good energy conditions. The results (Fig. 3, Anonymous 1975) show an upper, about 55 m thick, deposit with velocity of 1500–1600 m/s. This is characteristic of water-saturated sand, silt or clay. Underneath this layer is a 60–110 m thick layer with P-wave velocity 2100 m/s, which is usually interpreted as a typical water-filled till velocity. Underneath the till basement velocities of 4000–5000 m/s have been observed.

Vertical electric sounding (VES)

Pedersen (1978) interpreted a resistivity profile (RS-1) from Odbergmoen (Figs. 1 and 4). He found, below the soil, a 27 m thick highly resistive top layer (4400 Ωm), which he interpreted as mostly dry sand. Underneath was a 57 m thick rather conductive layer (22 Ωm) which obviously is marine (silty) clay. Similar interpretations are given for the other electrical soundings (Fig. 5). The VES results and the seismic results are consistent for the upper layers, but it is clear that the VES instrument (standard ABEM terrameter)

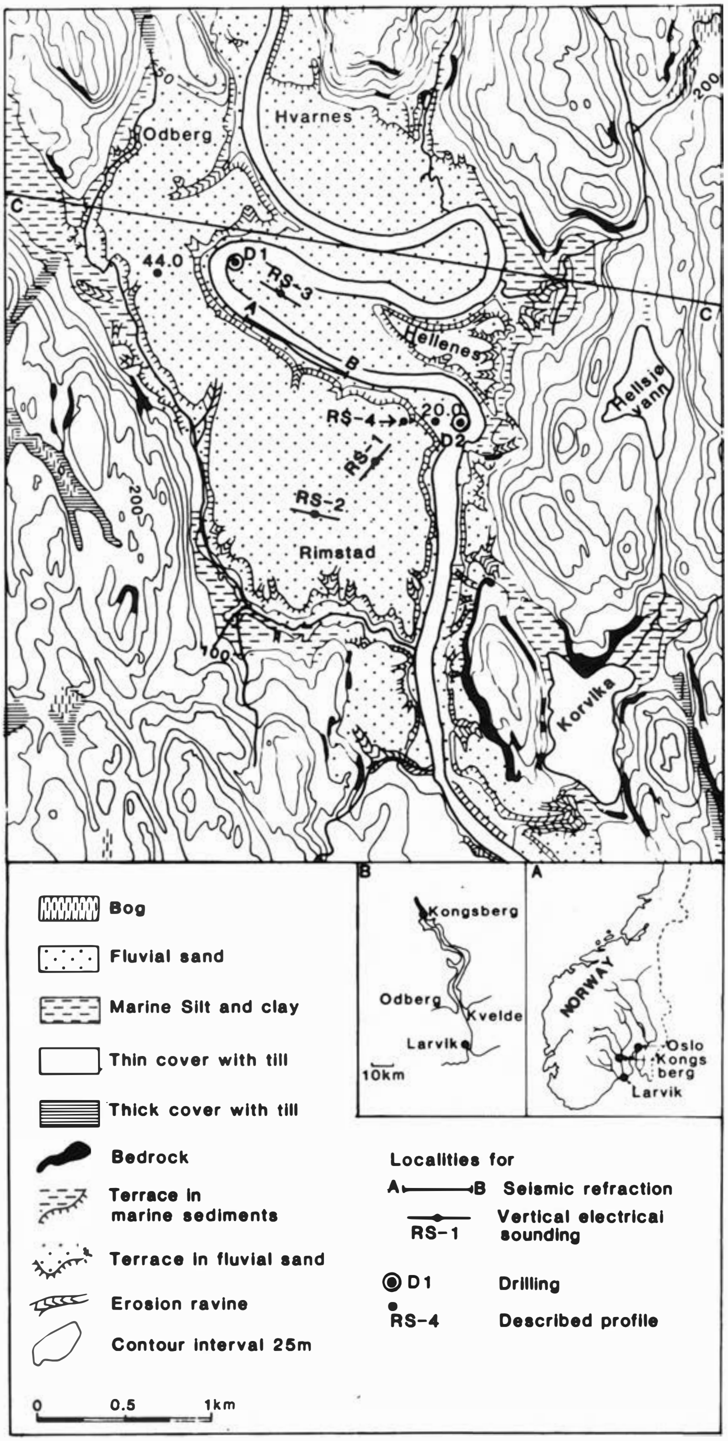

Fig. 1. Map showing the pleistocene deposits in the Odberg area, and locations for geophysical work.

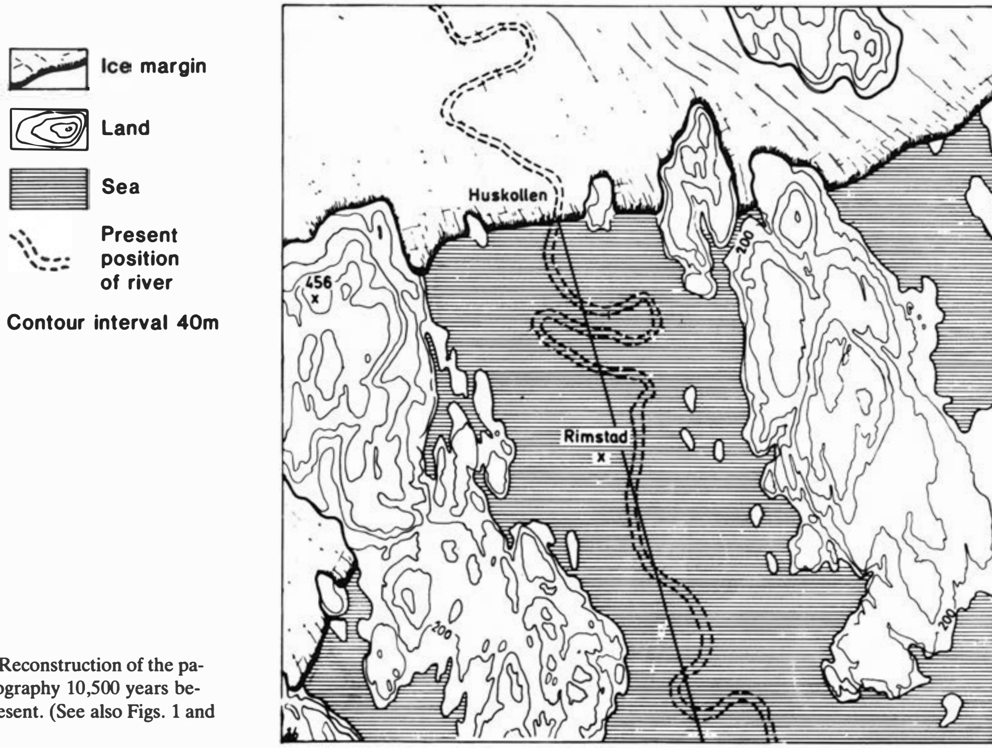

Fig. 2. Reconstruction of the palaeogeography 10,500 years before present. (See also Figs. 1 and 9).

did not have enough power to penetrate the till underneath the clay.

Above the water table there are an additional 30 m of sediments, consisting of an upper layer with dry sand above finer sediments which comprises the Odbergmoen terrace, 40 m a.s.l., cf. the sections RS 1–3, Fig. 5.

By combining geological and geophysical data, we conclude that in the middle part of this basin there is 25–30 m dry sand above approximately 60 m water saturated fine-grained marine deposits. Groundwater springs emerging a few metres above the river surface helps to define the boundary between these two sediments. Underneath the marine deposits is a 60–110 m thick till resting on basement. This lowermost till unit

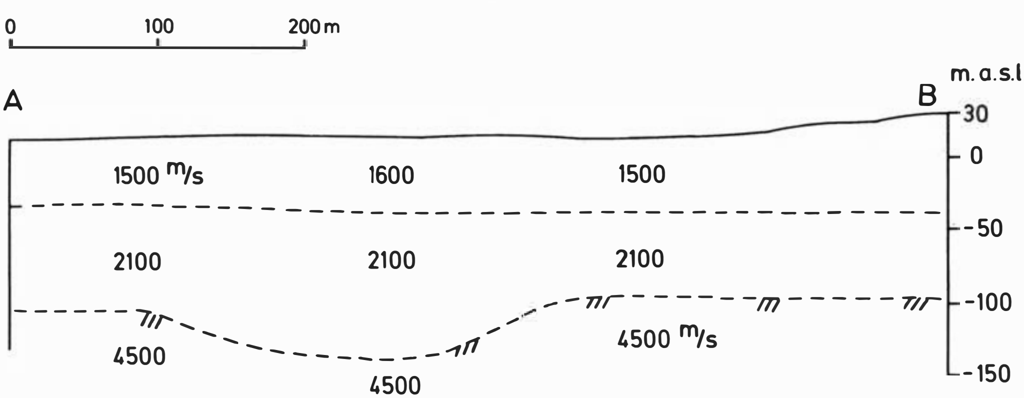

Fig. 3. Results from seismic refraction studies. Profile line A–B is shown on Fig. 1.

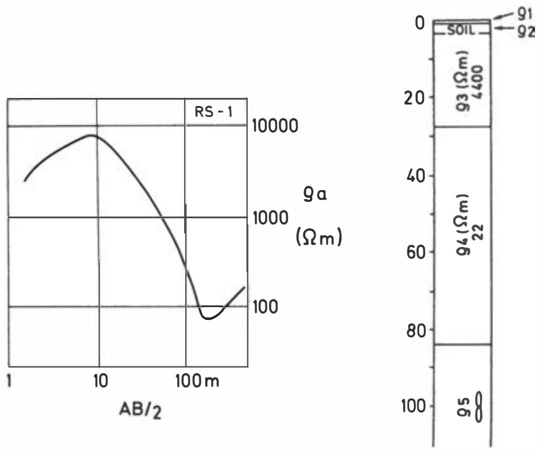

Fig. 4. Field data and interpretation of the vertical electrical sounding (VES) at locality RS-1 (Fig. 1).

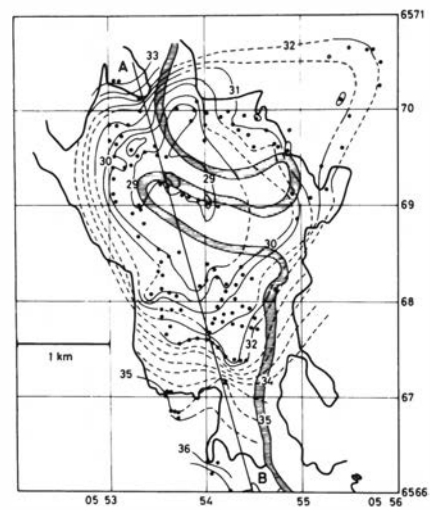

Fig. 6. Bouguer anomaly map (UTM coordinates). Present position of river Lågen shown with horizontal lines. Contour interval 0.5 mgal.

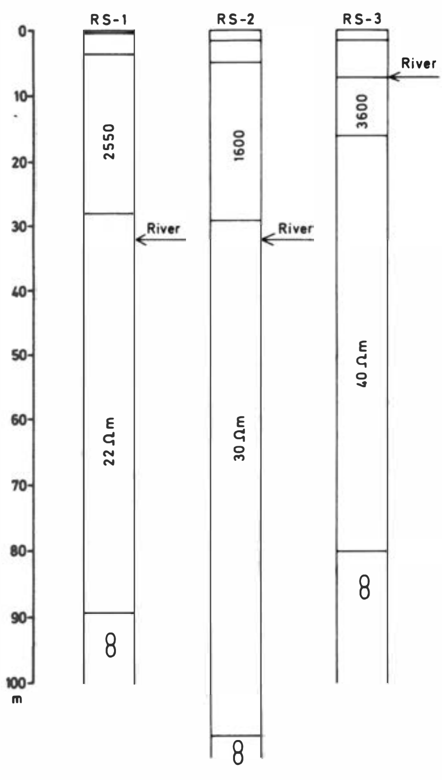

Fig. 5. Results from three vertical electrical soundings. Location on Fig. 1.

may be composed of several different layers, but we are not able to identify them with the methods used.

Gravity studies

Gravity measurements were done in order to get a three-dimensional picture of the thickness of the pleistocene deposits outside the area of the seismic profile (Fig. 6). The data were terrain-corrected, using the method of Grønlie & Ramberg (1973). The Bouguer anomalies show a 5 mgal low (minimum value 28.5 mgals) over the central parts of Odbergmoen. The gravity gradient follows the valley sides rather closely, thereby indicating a rather thick and uniform (flat-bottomed) sediment-filled basin. The gravity data also indicate that two basement highs are present, one at each end of the basin.

Density contrasts

Løken (1966) measured the density of silty clay continuously in a 27 m deep hole and found it to vary between 1.74 and 1.91 t/m^3 with an average density of 1.82. The increase was approximately linear from 7.5 m to 26 m. Bearing in mind a certain amount of compaction because of the overburden of nearly 30 m dry sand, we have used 1.85 t/m^3 as average density for the clay when doing the gravity modelling.

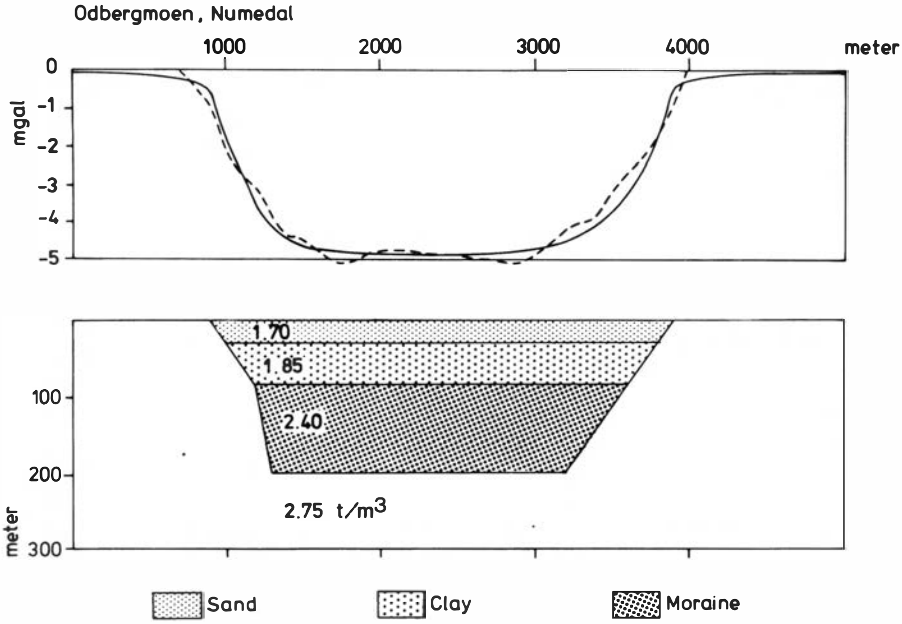

Fig. 7. Residual gravity profile and suggested sedimentary interpretation, based on gravity data.

The density for dry sand was calculated assuming a porosity of 40 % and allowing for some wet sand towards the bottom of the sand layer immediately above the clay. Dry sand with this porosity has a density of 1.64 t/m^3 (assuming a matrix density of 2.74 t/m^3), and we have used 1.70.

We have used 2.40 t/m^3 as density of the saturated till corresponding to a porosity of 20 %. Grønlie & Jørgensen (1974) used 2.43 t/m^3 as till density, while Jørgensen (unpubl.) found 2.1–2.3 t/m^3 with an average of 2.2 when measuring 50 samples from Norwegian tills. However, we assume the latter value to be too low, because the samples studied were not all totally saturated. The bedrock in the area consists mostly of plutonic rocks and we have used 2.75 t/m^3 (Ramberg 1976) in our model calculations.

Model study

A residual gravity profile (Fig. 7) was constructed along a NNW-SSE line in the middle of the valley. The line was chosen where the best regional control was found, using our and Ramberg's (1976) regional gravity data. The residual anomalies are maximally about -5 mgals along the central portion of the basin, with rather steep gradients at each end. We have constructed a three-layer model consisting of 27 m dry sand ($\nabla \varrho$ = -1.05 t/m^3), 58 m of clay ($\nabla \varrho$ = -0.90 t/m^3) and a third layer consisting of water-filled till ($\nabla \varrho$ = - 0.3 t/m^3). The two upper layers are taken from the seismic and VES results. The bottom layer overlying basement was manipulated until the difference between observed and computed gravity effect was acceptable (i.e. a visual good fit). The result, approximately 115 m of till throughout the valley, is in agreement with the seismic results within error limits. The seismic profile (Fig. 3), which is perpendicular to the gravity profile, shows 60–100 m till covering basement and is situated close to the 2000 m mark in Fig. 7. The gravity model being in agreement with the other data thus shows that the total amount of sediment infill was abut 200 m all over the basin, and that the basement floor in the valley must be rather flat.

Sediments

In this region the normal sequence of sediments is glacio-marine clay lying directly on bedrock, sometimes with a thin layer (0.5–1 m) of till or glaciofluvial material below the clay. This is also the case in a flat-bottomed part of Lågendalen

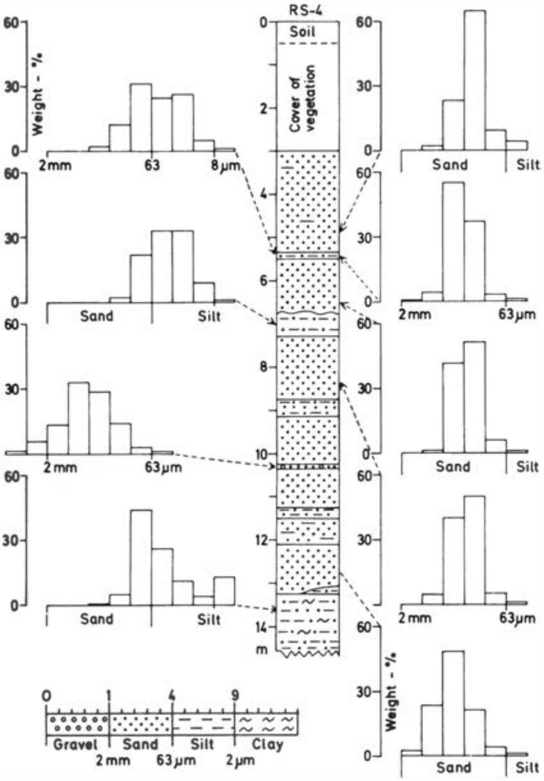

Fig. 8. Grain-size distribution in a section through postglacial fluvial sediments at locality RS-4 (Fig. 1).

some 20 km to the north (Korbøl & Sørensen, unpublished 1981). However, the glacially overdeepened basins in the Lågendalen valley represent quite different sedimentation environments from where no deep borings or other direct evidence are available.

The lowermost unit in the Odbergmoen area has been interpreted as a till. The only evidence available is the velocity from seismic refraction.

The clay unit normally consists of a lower *glacio-marine* and an upper *postglacial* clay (Feyling-Hanssen 1964). Both the glacial and the postglacial clays may be laminated; the former contains more sand and 'dropstones'. The latter consists mainly of silt with thin layers of fine sand and silty clay. Ten kilometres north of Odbergmoen we have found a sequence of 4 m postglacial clay with boreal molusc and foraminifera faunas over several metres of glacio-marine clay with high-arctic faunas. This section will be described in a forthcoming paper. The separation between glacio-marine and postglacial clay cannot be determined with the methods used in this study.

Most of the clays in the Odbergmoen area are covered by sand, which in places is more than 30 m thick. One section of the upper part of the sandy unit has been studied in detail (RS-4, Fig. 1 and 8). The composition of the upper 15 m varies between sand and sandy silt, but well-sorted sand dominates. The section shows plane layering/lamination with normal graded bedding in thin laminae in the middle part, otherwise structures are lacking. Variations in grain size and the layering may reflect yearly variations in sediment transport by the river. Most of the terrace, Odbergmoen, is built up of these layered estuary or fluvial sands deposited in the lower flow regime. Dynamic sounding with a rock-drill machine close to the river at two localities (D1 and D2 on Fig. 1) revealed more than 20 m with sandy sediments below the river. This may indicate that the sand had its maximum thickness in the central part of the valley, where it filled the clay-covered topography. Maximum thickness of sand in the central part of the basin, before erosion started, may therefore have been close to 50 m. An alternative explanation is that deep pools in the river have migrated as it meandered on the lower plain, and that the sand to a depth of 20 m below normal river level is infill in an erosion channel in the clay sediments. More than 15 m deep pools are found today in this strongly regulated river.

As the estuary rose above sea level, a braided river system was developed. Shallow erosion channels from this phase can be found on the terrace surface. Later, during continous sea-level lowering, the river started to meander and erode the estuary plain.

As the estuary moved southwards in the Lågen valley during the isostatic uplift, submarine clay slides, and bottom currents have been active, creating 'abnormal' sedimentation sequences or erosion.

Mass estimates

The length of the sedimentary basin at Odbergmoen is approximately 2.5 km (Fig. 1). The width of the anomaly is between 1 and 2 km, with an average of approximately 1.5 km. Thus a rough sediment mass estimate shows that close to 0.30 km^3 loose sediments were deposited above the thick till before river erosion started.

We have assumed that the whole basin was

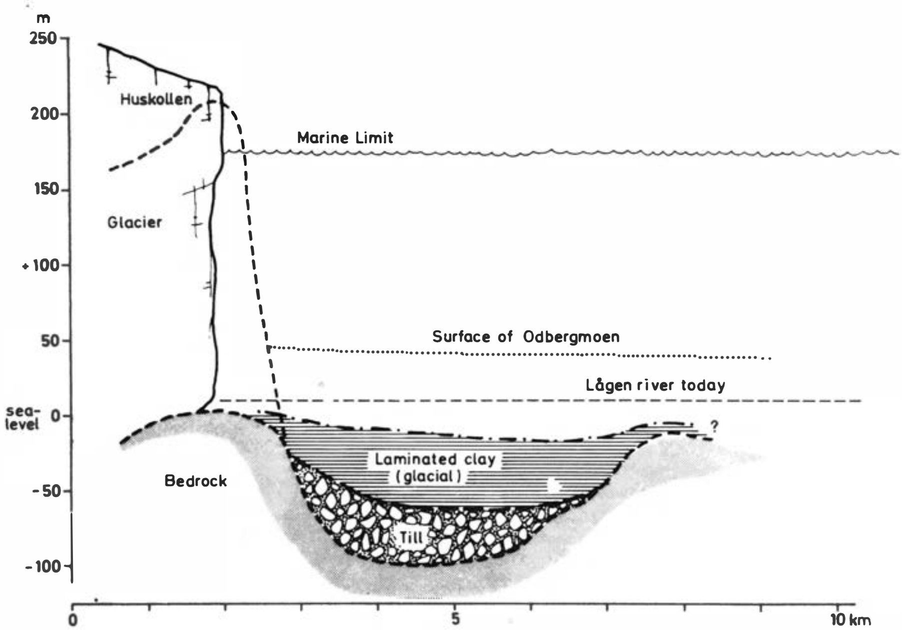

Fig. 9. Suggested reconstruction of glacier margin at Rimstad approximately 10,500 years ago.
Marine Limit: 175 m a.s.l., and position of glacier front, modified from Hassum (1967). The reconstructed glacier-front surface has been given an assumed gradient of 4%.
The stippled line at *Huskollen* represents a small mid-valley hill, see Fig. 2.

filled up to sea level at 7000 B.P. (40 m above the present level). These sediments were deposited mainly in two phases: As long as the glacier was present in the 'Lågendalen fjord' (10,500–9,500 B.P.) and during the time of estuary sedimentation (8000–7000 B.P., Jørgensen & Sørensen 1979). In addition, there was some deposition of marine sediments between these two phases. During the last phase mostly fluvial sand was deposited in the area, and the more fine-grained material was carried further to the south. It is not yet possible to estimate the amounts which passed or were eroded in the area during the mentioned time intervals. Average sedimentation rates within this basin were around 2.3 cm per year for the period from 10,500–7000 yrs B.P. However, a sedimentation rate of approximately 6 cm per year during phase one (see above), very low sedimentation rates during Late Preboreal and Boreal chronozones, and approximately 2.7 cm per year during the Early Atlantic chronozone (last phase above), is more compatible with geological evidence.

Discussion and summary

Active glaciers had eroded the valley bottom to about 150 m below present sea level, before the assumed till was deposited.

A suggested palaeo-environment model, with the glacier terminus just north of the Odbergmoen, is given in Fig. 9.

There is evidence for a major retreat of the inland glacier in this region during the latter part of the Allerød chronozone (unpublished data, R. Sørensen 1981), and the glacier may have retreated as far behind the 'Ra' position as Odbergmoen (ca. 15 km). Thus one can expect till from the Weichselian maximum, clay from Allerød, and 'deglaciation' (waterlain) till from the Early Younger Dryas chronozones. Since calving probably was important during deglaciation, it appears unlikely that the till was deposited during this period. Even older sediments could possibly be found at the bottom of the basin. However, the simplest model would be: tills from the Weichselian overlain by glacio-marine clay deposited while the glacier had a short stillstand at the narrow part of the valley just north of Odbergmoen (Figs. 2 and 9).

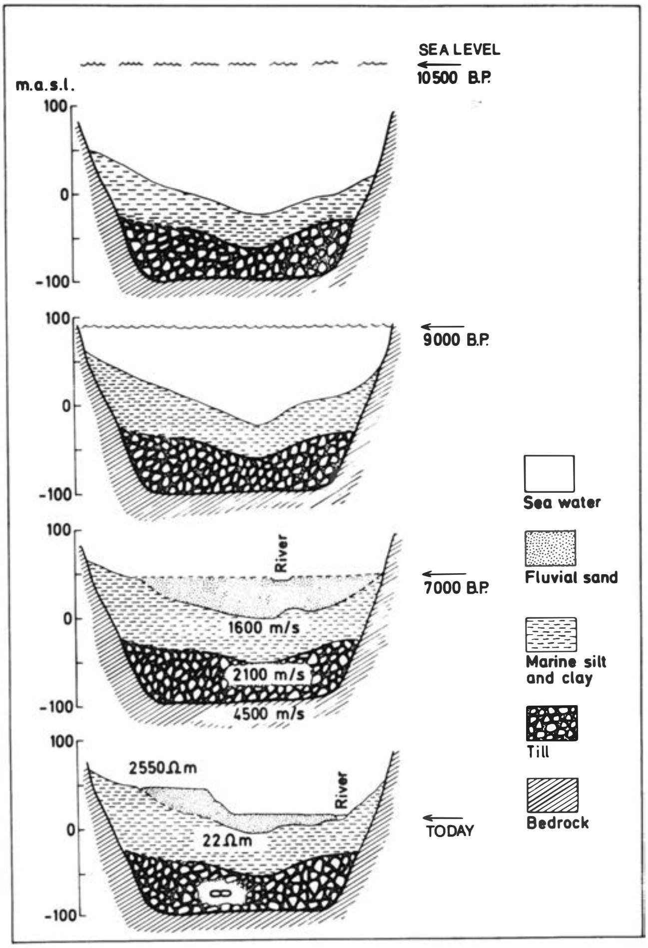

Fig. 10. Suggested stages in the glacial and postglacial development of the area studied. The profile chosen is shown on Fig. 1 by the line C–C. Seismic velocities and VES resistivities are given.

The ice front passed the studied area around 10,500 B.P., and the sea level was then around 175 m above present level (Figs. 9 and 10).

A fairly accurate estimate of the amounts of different sediments found in the studied area, has been obtained by combining geological and geophysical field work. Most probably there was a rapid sedimentation immediately after the deglaciation, with decreasing sedimentation rate as the icefront retreated further north.

During the next 3500 years there was, due to isostatic rebound, a gradual lowering of the sea level. The outlet of the river Lågen moved gradually southwards and large amounts of fluvial sand were deposited above the marine silt/clay deposits.

The upper accumulation levels for these sand deposits were determined by the sea level (Fig. 10). The surface of the large fluvial terrace Odbergmoen corresponds with the sea level approximately 7000 years ago. Sand carried by the river filled up the fjord and was built up to 40 m above present sea level.

This plain was lifted above sea level during the first part of the Atlantic chronozone. About 4000 years later the sea level had been lowered to the bedrock threshold at Holmfoss. The approximately 30 m deep erosion through the sediments in the Odberg basin took place during this period, and younger terraces were formed and eroded during the same period.

During the last 3000 years fluvial erosion and slides have increased the width of the erosion channel in the unconsolidated Late Weichselian and Holocene sediments.

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