Late Glacial and Holocene deglaciation and sedimentation in Lågendalen, southeastern Norway

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Jørgensen, P. & Sørensen, R.: Late Glacial and Holocene deglaciation and sedimentation in Lågendalen, southeastern Norway. *Norsk Geologisk Tidsskrift*, Vol. 59, pp. 337–343. Oslo 1979. ISSN 0029-196X.

At the end of the Ra period, approximately 10,600 years ago, the icefront retreated mostly by calving with intermittent stops through the long and narrow Numedalfjorden. Average recession rates lie between 90–100 m per year. Detailed mapping of Glacial and Postglacial sediments, combined with radiocarbon and geophysical data, allowed reconstruction of Late Glacial and Holocene development, dating of glaciofluvial and river valley terraces, and calculation of average sedimentation rate during Preboreal time in a deep ice-eroded basin.

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Deglaciation

The largest of the Younger Dryas moraines, the Ra, crosses the lower Lågendalen at Bommestad, northeast of Larvik (Fig. 1). A radiocarbon dating indicates an early advance to the Ra position around 11,000 B.P. (T-261, Andersen 1968). How far behind the Ra the glacier subsequently retreated during the Allerød period, when marine clays were deposited, has not yet been established.

The ice readvanced to the Ra around 10,700 B.P. Whole shells in a glaciomarine clay lying below disturbed bedded sediments and till near Sandefjord, have been dated to 10,650 ± 150 B.P. (T-426, Andersen 1968).

A glaciomarine clay with paired, whole *Macoma* shells, overlain by disturbed marine sediments and glaciofluvial gravel near Tønsberg, was dated to 10,850 ± 110 B.P. (Lu-716, Sørensen 1979). Based on this and other evidence presented below, it is assumed that the final retreat from the Ra took place around 10,600 years ago.

Several lateral and frontal deposits, mainly of glaciofluvial character, indicate a stepwise retreat of the glacier front up the valley from Larvik to Kongsberg (Fig. 1). The glaciofluvial deposits at Passebekk-Goverud have been tentatively correlated with the Ski event, which has been dated to 10,000–10,200 B.P. (Sørensen 1979). Mapping of the moraine ridges between Sande and Goverud has been done by Nygaard (1952). The Sande frontal deposits are most likely contemporary with the Ski moraines, which can be followed eastward to the Mona ridge at Mysen (Holtedahl 1974, Andersen 1975). The age of the large glaciofluvial deposits in the Kongsberg region will be discussed below.

Marine limits

The upper limit for wave-washing at Larvik is approximately 155 m a.s.l. Farther up Lågendalen the upper marine limit is at Svarstad 173 m a.s.l. (Korbøl 1972), 184 m a.s.l. at Goverud, and 175–177 m a.s.l. at Skollenborg (Marthinussen, *in* Holtedahl 1953). Field work in connection with the Numedal Project (Rosenqvist 1969) has verified the Skollenborg area value, while the stated marine limit at Goverud is probably 4–5 m too high.

Other marine limits used in this paper are the ones developed in the Ski moraine at Drøbak, 195 m a.s.l. (Sørensen 1979), and the Mona locality at Mysen, 208 m a.s.l. (Holtedahl 1974).

Equidistant shoreline diagram

A large number of glaciofluvial and fluvial (river valley) terraces are found in the valley from Larvik to Kongsberg. For estimating the approximate time of formation of these terraces an equidistant shoreline diagram was constructed (Fig. 2). The diagram is parallel to line A–A on Fig. 1.

In addition to the datings and marine limit determinations already mentioned, the diagram

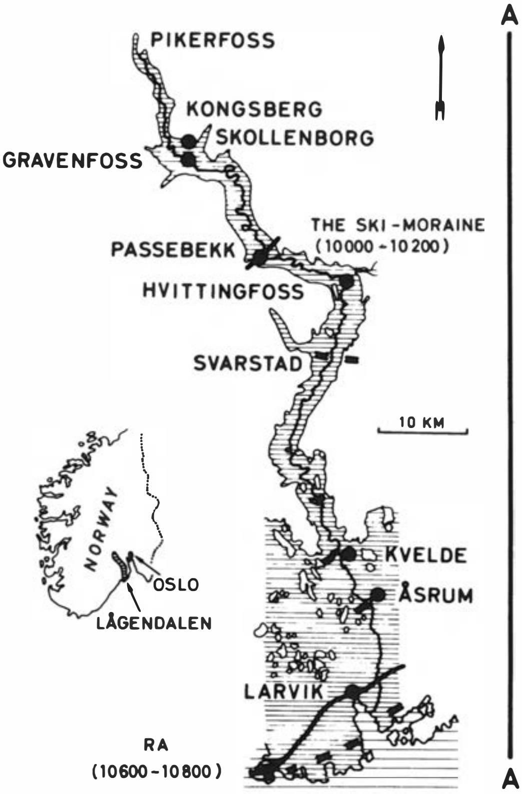

Fig. 1. Key map showing the most important localities. Numedalfjorden, from Kvelde to Pikerfoss, existed during the Boreal chronozone.

(Fig. 2) is based on the following data. Two radiocarbon datings of an isolation contact 32 m a.s.l. at Gogsjø give a reliable position for the '5000 years line' in the diagram (Nydal 1959). The shoreline gradients and the position of the older lines in the diagram (Fig. 2) have been transferred from a similar diagram constructed for the area east of Oslofjorden (Sørensen 1979).

The lines in the diagram have been given approximate ages with a deviation of ± 100 years. For the older lines this represents an uncertainty in height of 5–10 m, while for lines younger than 7000 B.P. the uncertainty is 2–3 m. These uncertainties in the diagram are reasonable with the present state of knowledge of sea-level changes in the region.

Deglaciation deduced from the shoreline diagram

The first large glaciofluvial deposits in Lågendalen north of the Ra are found at Styrvoll and Svarstad (Fig. 2) These are thought to represent short stops in the recession of the glacier. The approximate age of the Svarstad glaciofluvial deltas is 10,300 B.P., and the Styrvoll deposits are slightly older. An approximate recession rate for this Ra-Svarstad phase is calculated as 100 m per year. The Svarstad deposits are tentatively correlated with the Ås event (Sørensen 1979). From Svarstad to Passebekk the average recession rate was slightly less than in the preceding phase, about 90 m per year. Between Passebekk and the large glaciofluvial deltas at Skollenborg and Heistadmoen a rate of 85 m per year has been calculated. The Skollenborg delta is correlated with the Aker event.

The highest terraces at Pikerfoss (Fig. 3) are close to 100 years younger than the Skollenborg delta, and on average the ice-front in this narrow part of the valley retreated 100 m per year.

On the eastern side of Oslofjorden a similar recession pattern has been observed (Sørensen 1979). The glacier retreated fairly rapidly from the Ra to the Ås and Ski moraines (Fig. 1). The Ås and Ski events are characterized by numerous brief stops in the recession, and especially the largest of the Ski moraines shows evidence of a readvance. After the Ski event the glacier receded rapidly to the Aker moraines north of Oslo.

Considering the topography of Lågendalen and the position of the bedrock thresholds in the river profile (Fig. 2), one might assume a rapid retreat by calving from the Ra to the threshold at Kjerrafossen falls. During a short stop there the lateral glaciofluvial delta at Styrvoll was formed.

The Svarstad deposits were also probably formed during a short stop caused by a bedrock threshold, while the Passebekk locality seems to have been controlled by glaciological factors. Consequently the glacier terminus may have been stationary at Passebekk for a number of years, similar to the Ski event in the Oslofjorden area.

From Passebekk towards Skollenborg (the Labrufoss threshold) there was most likely rapid recession through calving, because the valley opens up to the north of Passebekk and the basin itself is considerably overdeepened (Fig. 4). The average recession rate calculated for this part of

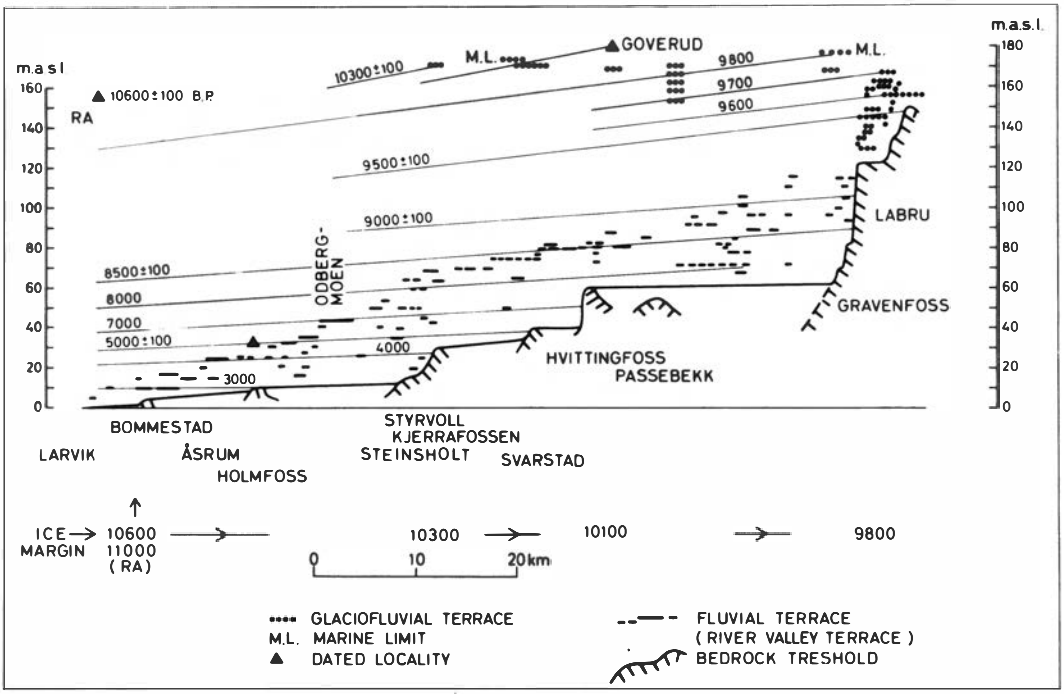

Fig. 2. Profile along the river Lågen from Larvik to Gravenfoss showing bedrock thresholds and elevation of glaciofluvial and fluvial terraces. Equidistant shoreline diagram for the last 10,600 years is superimposed. The profile is parallel to line A–A on Fig. 1.

the valley may therefore have little meaning. From Skollenborg to Pikerfoss (Fig. 5) there is considerable evidence for dead-ice wasting, and it is difficult to define an actual glacier front retreat.

Holocene sea level changes in Lågendalen

The sea followed the retreating ice-front, and the long narrow Numedalsfjorden reached from Kvelde to Skollenborg (Fig. 1) in late Preboreal-early Boreal time. Material carried by meltwater was deposited as glaciofluvial deltas in the inner part of this fjord (Heistadmoen, Saggrenda and Skollenborg, Figs. 3 and 5). About 9800 years ago, when the ice had receded to Kongsberg, the sea level was 176 m a.s.l. at the ice terminus. With a shoreline gradient of 0.75 m/km, the corresponding sea level at Larvik would have been 125 m a.s.l.

The isostatic rebound attained its maximum during the next 300 years with a corresponding relative sea level lowering of at least 35 m (Fig. 2). Consequently, by 9500 years ago, sea level was approximately at the level of the rock threshold at Kongsberg (Fig. 5). About 300 years later the river had cut down through the large glaciofluvial terraces between Kongsberg and Skollenborg, and the erosion base was then controlled by the rock threshold at Labrufoss. Between 100–105 m a.s.l. remnants of a few terraces are found outside the delta front at Skollenborg. These are all older than 9000 B.P.

From 9000 to 8500 B.P. a number of terraces were lifted from sea level and above, since the sea dropped approximately 18 m during this first half of the Boreal chronozone. The highest number of terraces in Lågendalen were lifted above sea level during the latter half of Boreal time. The drop in sea level amounted to 14–16 m, and the sea regressed relatively quickly from Gravenfoss to Hvittingfoss (Fig. 2).

An important consequence of these sea level changes was the fact that all the sediments used in building up the terraces above the '8000 years B.P. line' (Fig. 2) must have been transported to

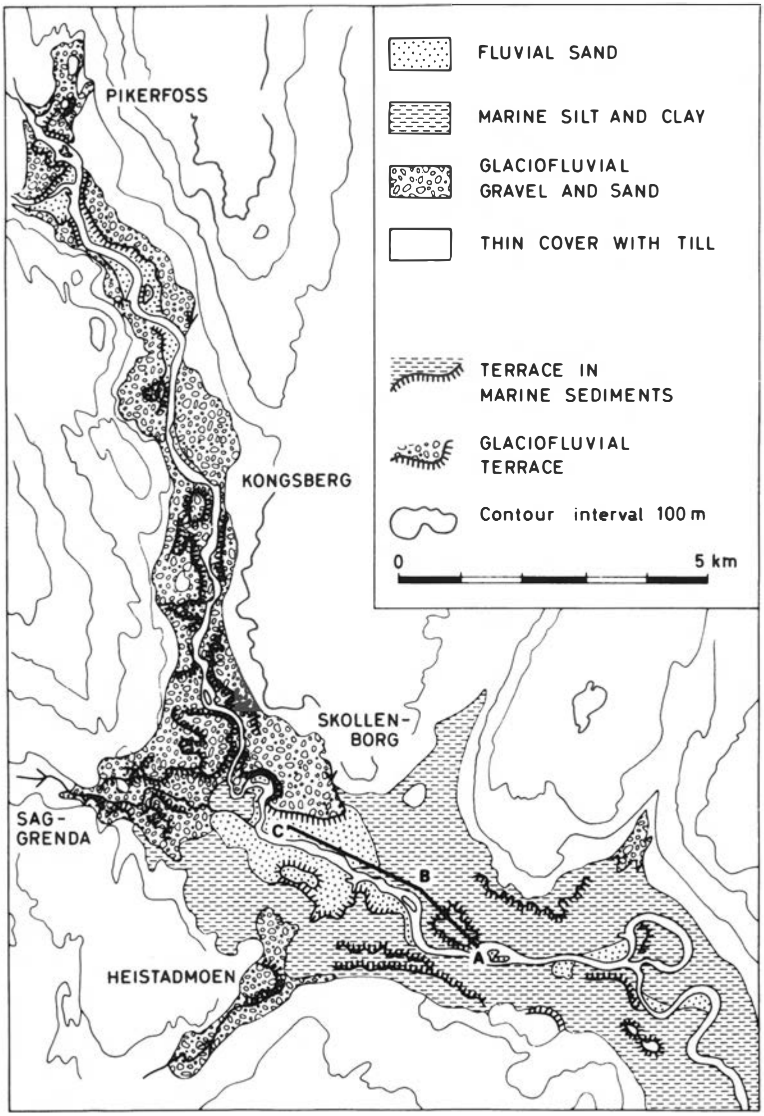

Fig. 3. Sediments deposited in Numedalfjorden. Marine limit in the Kongsberg area is 176 m a.s.l. Line A–B–C is a seismic profile line.

Lågendalen during Preboreal and Boreal time. This is reasonable since farther inland Hardangervidda was ice free at the end of the early Boreal subchronozone (Sandmoe 1960) and remnants of the ice sheet were found only in the valleys north of Kongsberg. Considerable amounts of sediments were still being supplied to the sedimentation basins, but at the end of the Boreal chronozone the meltwater discharge was probably insignificant and the generally dry climate must have resulted in a marked drop in annual river sediment discharge.

The surface of one of the largest fluvial terraces in Lågendalen, Odbergmoen, corresponds with the sea level of 7000 B.P. Except for Odbergmoen, relatively few terraces were lifted above sea level during the wet Atlantic chronozone. At the end of Subboreal time the sea had withdrawn to outside Bommestad, where the Ra still functions as a local erosion level. As in Boreal time, during a dryer climate, better defined terraces were lifted above sea level also in Subboreal time.

It appears as if sediment transport was at a maximum during wet periods, and the deposits formed during these periods were lifted above

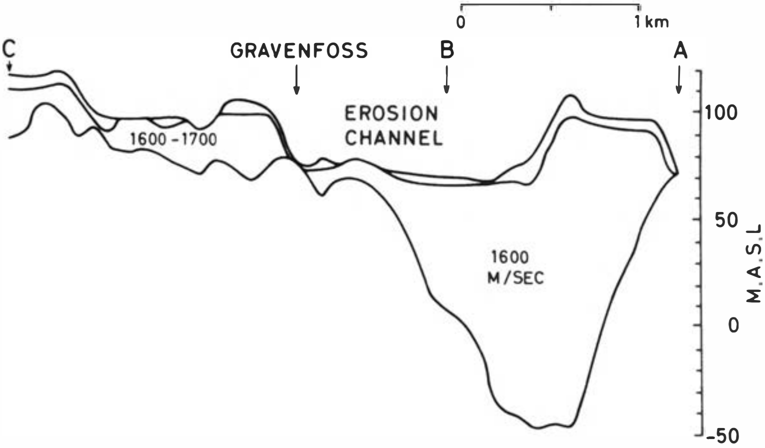

Fig. 4. Depth and seismic velocity of sediments deposited in Numedalfjorden. Seismic profile line A–B–C is shown on Fig. 3. The large erosion channel was probably formed during the Boreal chronozone.

sea level during the dry periods, to become terraces. The lowest terrace surface south of Bommestad corresponds to the sea level at the Subboreal/Subatlantic chronozone transition.

Sedimentation in the Kongsberg area

Between Skollenborg and Pikerfoss several glaciofluvial terraces are found (Figs. 3 and 5). The bulk of the sediments is sand and gravel, and frequently a very coarse upper cobble layer can be observed. Particle size and sedimentary structures reveal that these sediments were deposited in a high velocity stream regime.

Distinct dead-ice phenomena, such as kettle holes, bear witness to the ice-contact nature of the deposits. If all these terraces had been deposited at the same time, the upper accumulation surface would increase more than 25 m from Heistadmoen to Pikerfoss, due to isostatic rebound. Since this is not the case (Fig. 5), it is natural to conclude that the glaciofluvial deposits in the 'dead-ice zone' were deposited during a gradual retreat of the ice. Consequently, when the terrace material at Pikerfoss was being deposited, the river had already eroded about 20 m into the Kongsgårdmoen-Skollenborg terraces. It is important to remember that only 600 years were available for dead-ice wasting, glaciofluvial deposition, and subsequent fluvial erosion down to the erosion base level of Labrufoss.

Silt and clay were laid down in deeper parts of the fjord simultaneously with the glaciofluvial deposition. As already pointed out, a large over-deepened sedimentation basin exists just south of Skollenborg (Fig. 3). Using seismic methods, the depth to bedrock has been determined (Geoteam A/S 1977, internal report). The profile line is shown on Fig. 3 and the results are given in Fig. 4. The maximum depth to bedrock between A and B is 160 m and the seismic vel-

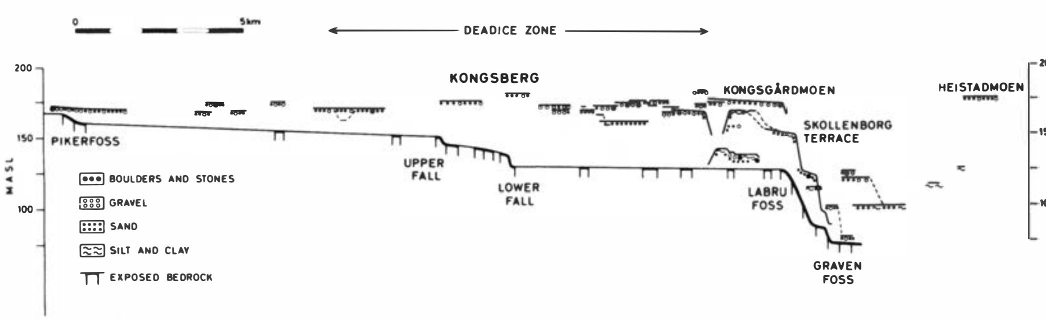

Fig. 5. Profile along the river Lågen from Pikerfoss to Gravenfoss showing elevation of the river bed and of the glaciofluvial terraces.

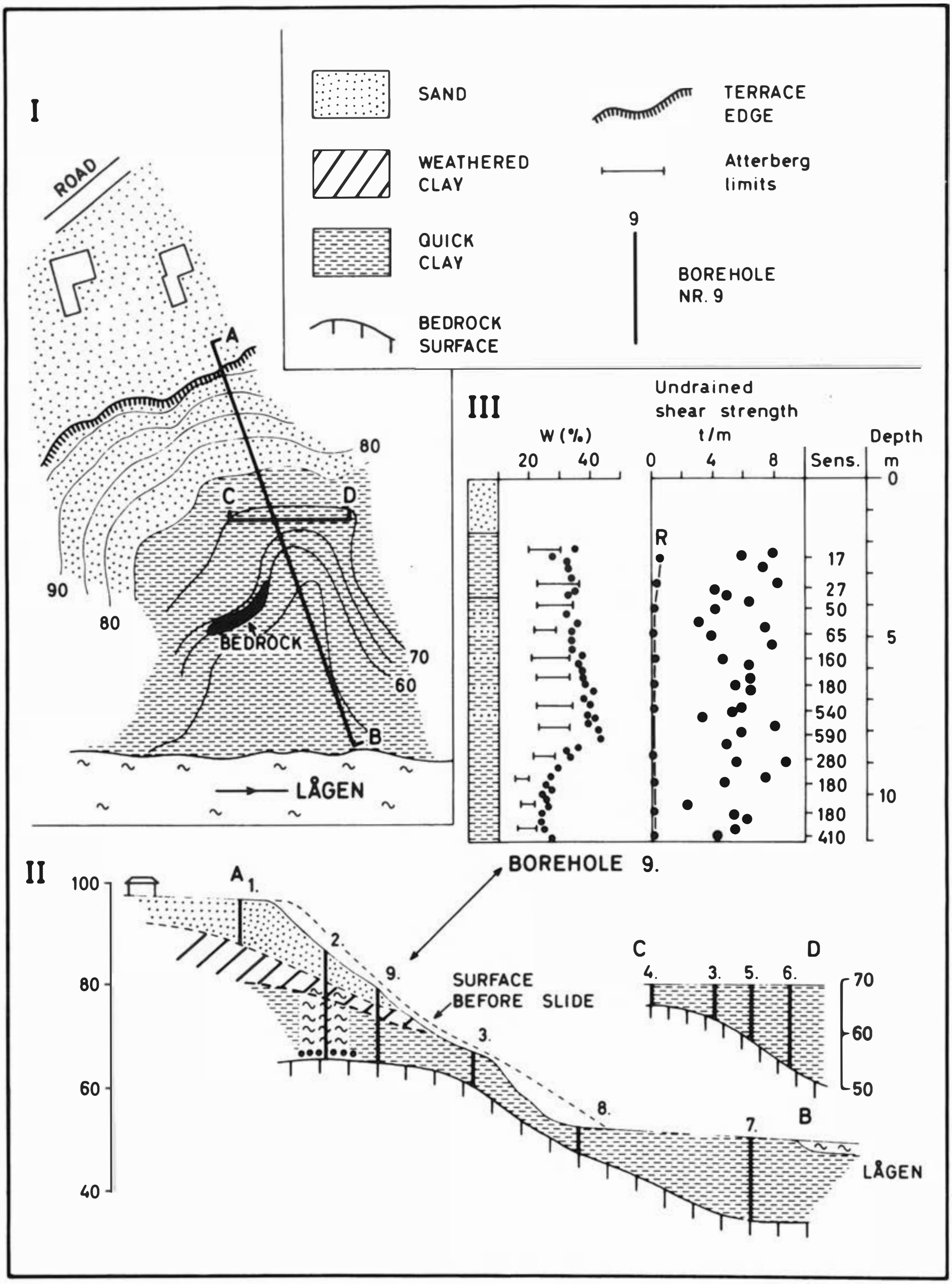

Fig. 6. Section through sediments at Hvittingfoss. Geotechnical data are from an internal report of Norges geotekniske institutt.

ocities indicate that this deeply ice-eroded basin is filled with fine-grained deposits. The upper 30 m of these sediments are exposed in an erosion channel which probably formed during the first half of the Boreal chronozone. The sediments are composed of 'varved' layers of alternating clayey silt and sandy silt. Since erosion in these sediments started about 9000 B.P. (Fig. 2), the maximum time available for deposition was 1000 years (from when ice-front retreated, about 10,000 B.P.). Consequently, the average deposition rate for the deepest part of this basin was around 17 cm per year.

Sedimentation and postglacial processes in the Hvittingfoss area

Fig. 6 shows a section through the sediments deposited just south of the Hvittingfoss threshold (Fig. 2). The height of the sandy terrace, 97 m a.s.l., corresponds with the sea level of 9000 B.P. It seems reasonable to assume that the valley, from Gravenfoss to the very narrow cross-section at Steinsholt (Fig. 2), was filled to this level with sediments. A major part of the glaciomarine sediments was probably deposited during the ice recession, while the sandy top-sediments were deposited during the first 800 years of the regressive period.

Further lowering of sea-level caused erosion into these sediments and the present river elevation was established about 7500 years ago.

Geotechnical studies have shown that the clays have high sensitivities (ratio between shear strengths of undisturbed and remoulded samples). The scattering of the observed values for undisturbed shear strength (Fig. 6) must be attributed to the high sensitivities and accompanying problems for obtaining so-called undisturbed samples. High sensitivity is generally attributed to the removal of salt (Rosenqvist 1955), which has caused a lowering of liquid limit below the natural water content (Fig. 6). Diffusion alone cannot explain the salt removal and consequently it must be assumed that hydraulic flow is responsible for the salt removal. This process started when the bedrock along the valley was lifted above sea level and infiltration of precipitation built up the hydraulic gradients necessary for this flow.

Due to postglacial weathering, podzol profiles have developed in the sandy deposits contemporarily with weathering of the clay just below the clay/sand boundary.

The Hvittingfoss area demonstrates that clay slides have been an important factor in the forming of Lågendalen in Holocene time, together with fluvial processes such as river bank erosion and extensive ravination by small streams.

Acknowledgements. – The support of The Norwegian Research Council for Science and the Humanities (NAVF) is gratefully acknowledged. The authors also express their appreciation to Professor Ivan Th. Rosenqvist for all help received in connection with the Numedal Project. We wish to thank A/S Geoteam and Norges geotekniske institutt for permission to use data from their internal reports.

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