Stratigraphy and sedimentation of a terminal moraine deposited in a marine environment – two examples from the Ra-ridge in Østfold, southeast Norway

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The stratigraphy of the Ra-ridge, a marine terminal moraine of Younger Dryas age, was studied in two large gravel pits at Vister and Bjørnstad. Glaciofluvial sediments in foreset beds dominate. Till beds overlie the foreset beds, or they are interbedded with them. Several different processes were involved in the deposition of the tills, such as lodgement, melt-out and flow processes. All beds were deposited below sea level at or near a grounded glacier front. Phases when the glacier was located to the north (up glacier) of the moraine are represented by beds of fine-grained glaciomarine sediments. Folds and faults are evidences of an overriding and/or oscillating glacier front. The stratigraphy shows that the glacier front oscillated more during formation of the Ra-ridge at Vister than at Bjørnstad.

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Stratified marine terminal moraines are found at numerous localities along the coast of Norway, and many of them are of Younger Dryas age. They are correlated with the Ra-moraines in the Oslofjord region. However, almost no detailed studies have been carried out on the stratigraphy of these kinds of moraine. Several general descriptions have been presented, in particular of the Ra-ridge (Holtedahl 1953; Andersen 1968, 1975, 1979; Andersen et al. 1981, 1982).

The aim of our study was to examine in detail the stratigraphy in two well-exposed sections in the Ra-ridge, in order to draw conclusions about the depositional environment.

The Ra-ridge (Raet) is dated to 11,000–10,700 years BP according to Sørensen (1983). Most of the ridge was deposited below sea level, and lies on both sides of the Oslofjord as a well-defined ridge (see Fig. 1). The examined sections of the ridge lie on the eastern side of the fjord and they are two of the best exposures of this kind in Norway. The section from Bjørnstad gravel pit (BGP) in Tistedalen near Halden (see Fig. 1), covers the distal, central and partly the proximal parts of the ridge, which at this site is about 20 m high and 150 m wide (Karlsen 1986). The section from Vistergropa gravel pit (VGP) in Tune (see Fig. 1) covers the distal and central parts of the ridge, which here is about 30 m high and 1200 m wide (Heder 1987). Major emphasis has been put on the sedimentological studies of the diamictons and their relation to the other units.

In Tistedalen the marine limit (ML) is 175 m a.s.l. (Holmsen 1951; Holtedahl 1953; Karlsen 1986), and the crest of the ridge at Bjørnstad lies 100 m a.s.l. The crest of the ridge at Vister lies 85 m a.s.l. and an isobase map worked out by Sørensen (1982, unpubl.) indicates that ML is about 185 m a.s.l. The Ra-ridge represents a dis-

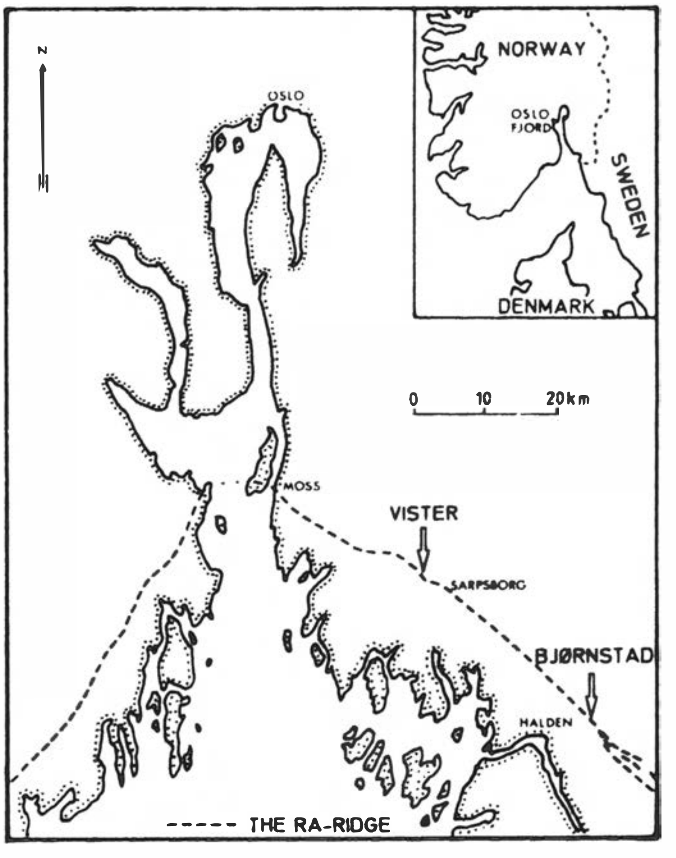

Fig. 1. Location map. Dashed line: the Ra-ridge.

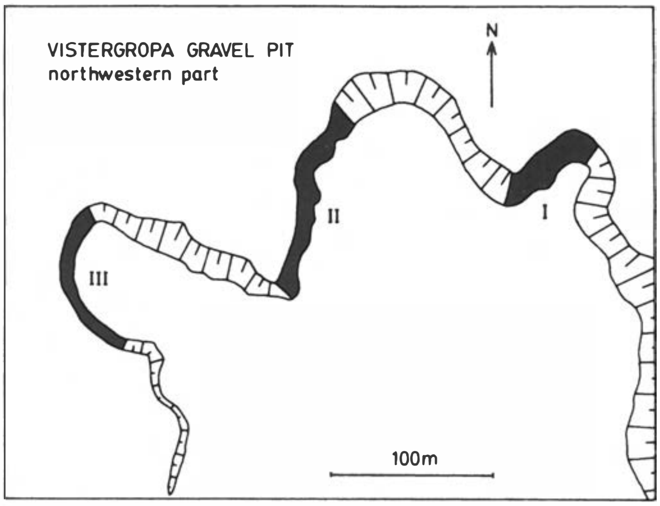

Fig. 2. Northwestern part of Vistergropa gravel pit with the three studied sections shown in black.

tinct landscape feature, with nearly bare bedrock to the north, and plains covered with marine sediments to the south. The bedrock in the investigated areas consists almost entirely of Precambrian gneisses and granites.

Few of the studied sections contain fossils. Therefore, the investigations are based on lithological studies using methods like grain-size analysis (Folk & Ward 1957; Folk 1966), roundness analysis (Olsen 1983), fabric analysis (Olsen & Hamborg 1983; Mark 1973, 1974) pebble counts, studies of sand-grain morphology with scanning electron microscope (SEM) (Strass 1978; Krinsley & Doornkamp 1973; Whalley & Krinsley 1974) and detailed studies of structures. In describing the units in the two sections, we use the same letter notations as Andersen (1979). He used letters A through H, going from youngest to older sediments, to describe different units of a marine terminal moraine in general.

Vistergropa gravel pit

The examined section in Vistergropa (VGP) consists of three parts where the beds were well exposed (see Fig. 2). Fig. 3a shows the three parts linked together in a stratigraphic model and divided into seven units from A to G (see also Figs. 3b and 3c). The section is 280 m long and up to 22 m high. The most important constituents are: (1) sand and gravel in foreset beds, (2) sandy diamictons in lenses and beds, and (3) beds of fine-grained, poorly sorted glaciomarine sediments.

Unit G. Only the upper 4 m of this unit was exposed, and it consists of alternating beds of moderately well-sorted sand and sand beds with approximately 35% silt and clay. The beds are generally 3–6 cm thick and they dip 2–4° SW, i.e. in distal direction. The unit also contains isolated clasts of fine gravel. Shells of *Macoma calcarea* were observed, but they were partly disintegrated except for one specimen. Unit G contains foraminifera, but only 133 specimens in a 950 g sample. The three coldwater species, *Nonion labradoricum* (48.1%), *Elphidium excavatum* (29.3%) and *Cassidulina reniforme* (17.3%), constitute 95% of the fauna.

The fauna, the stratification and the scattered coarse clasts show that the beds are glaciomarine, and deposited not very far from the glacier in a period before it advanced to deposit the Ra-ridge. The estimated age of unit G is ca. 11,000 years BP, based on ^{14}C dates of the Ra-moraine (Andersen 1968; Sørensen 1979). However, a ^{14}C date of *Macoma calcarea* (T–6901) gave an age of 9,730 ± 240 BP, which must be wrong. According to seismic lines and information from drilling carried out by the Geological Survey of Norway (Robertsen 1987), there are some 16 m of sediments from the floor of the pit down to the bedrock. The upper 10 m consists of sand which probably represents a lower part of unit G, while the

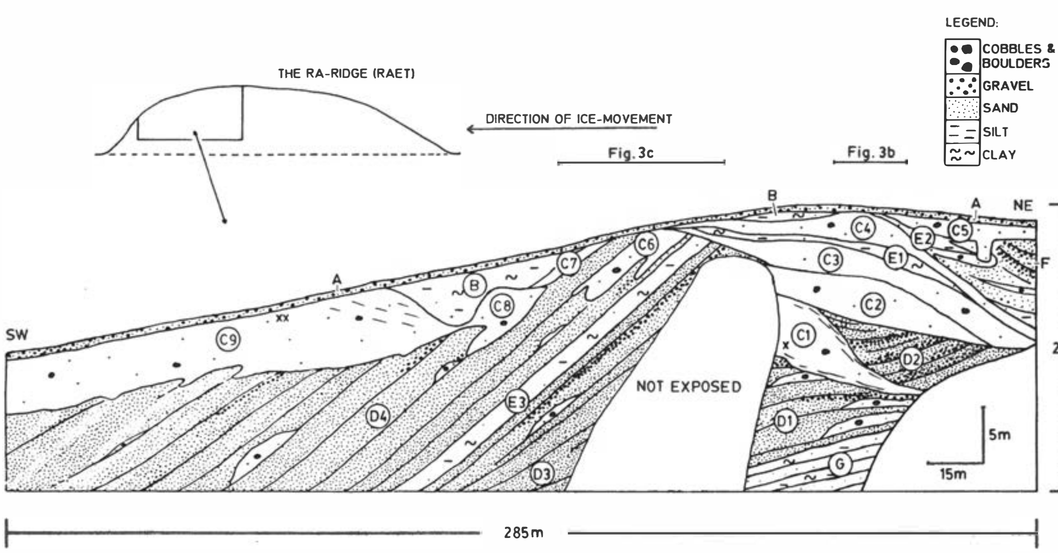

Fig. 3a. Cross-section of the examined units in Vistergropa gravel pit (VGP). Note: exaggerated vertical scale. A: shore sand and gravel; B: postglacial marine deposits; C: till beds; D: foreset beds; E and G: glaciomarine beds; F: glaciofluvial gravel beds; X: location of fabric analysis Fa-2; XX: location of fabric analysis Fa-3 (see also Fig. 4).

underlying 4–5 m consists of clays which apparently correspond with unit H, described by Andersen (1979). Unit H consists of marine beds older than the terminal moraine.

Unit F is 4.5 m thick and consists mainly of sand and gravel beds dipping in proximal direction. Since the beds are not well exposed, we refer to the description and conclusions for unit F from Bjørnstad gravel pit.

Unit E consists of three beds, E1–E3, up to 3.2 m thick. Bedded, poorly to very poorly sorted deposits of sand, silt and clay dominate in all beds. Sand beds are most common, but some layers consist mainly of silt and clay. Isolated gravel clasts and cobbles, probably ice-rafted, occur in most beds, and tiny folds and faults were observed within the laminated parts of E1 and E2. Flame structures were observed in the lower, uphill part of E3. The structures suggest a drag caused by the movement of the overlying beds in distal direction (Fig. 4), and they can possibly be connected with a glacier advance or a synsedimentary deformation. Foraminifera or macrofossils were not found in the unit, but imprints of the mollusc *Macoma calcarea* were observed in bed E3.

The beds in unit E are glaciomarine bottomset beds, probably deposited in periods when the glacier had retreated some distance from the Ra-ridge.

Unit D is the dominating unit in the section. It is divided into four parts, D1–D4, where D4 is up to 14 m thick. Unit D consists of foreset beds which dip 10–15° in a SW direction. They are beds of sand and gravel, with beds of sand as the most common. The sand is up to moderately well sorted ($\sigma 1 > 0.6$). The gravel beds contain 10–20%

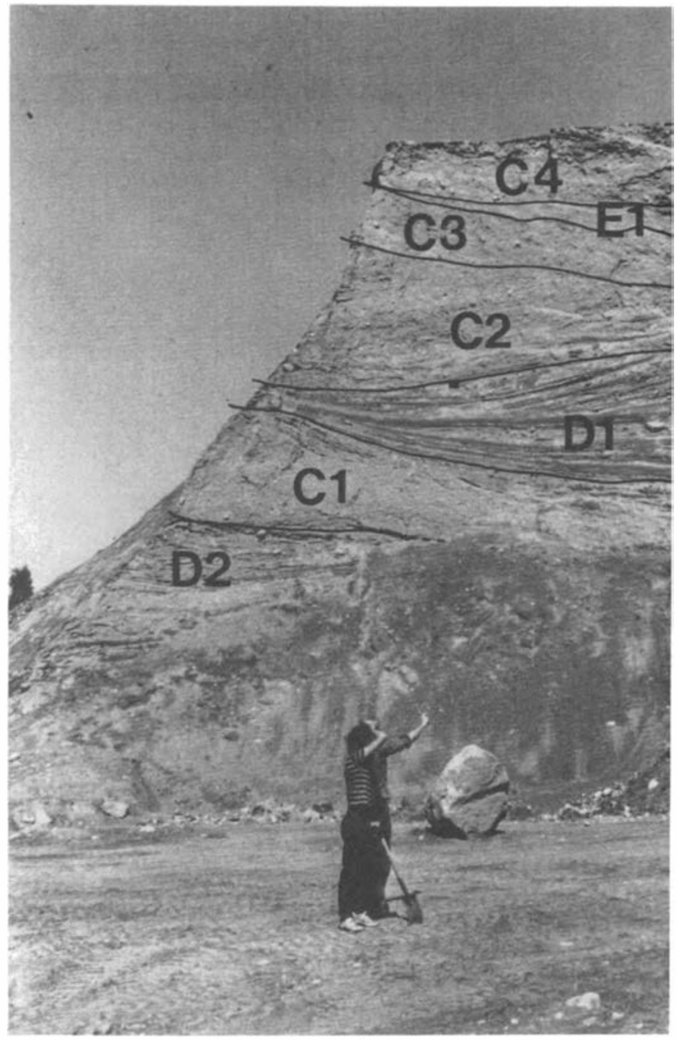

Fig. 3b. Picture from the proximal part of the examined section in Vistergropa. C1–C4: till beds, D1–D2: foreset beds, E1: glaciomarine bed.

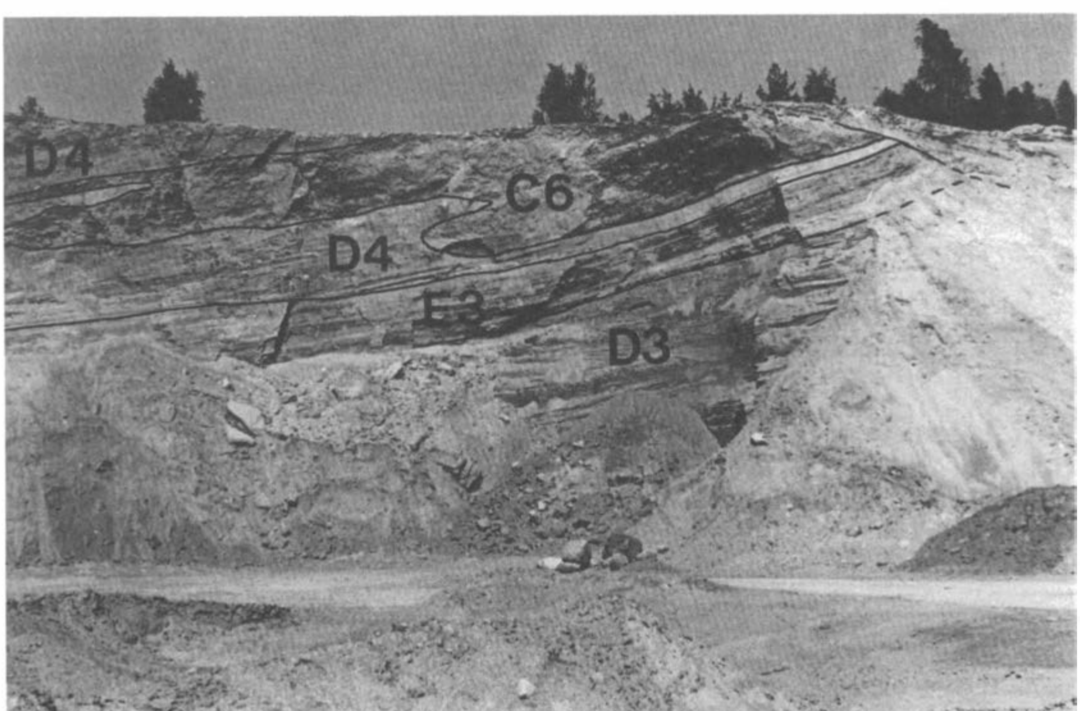

Fig. 3c. Picture from the central part of the examined section in Vistergropa. C6: till bed, D3–D4: foreset beds, E3: glaciomarine bed.

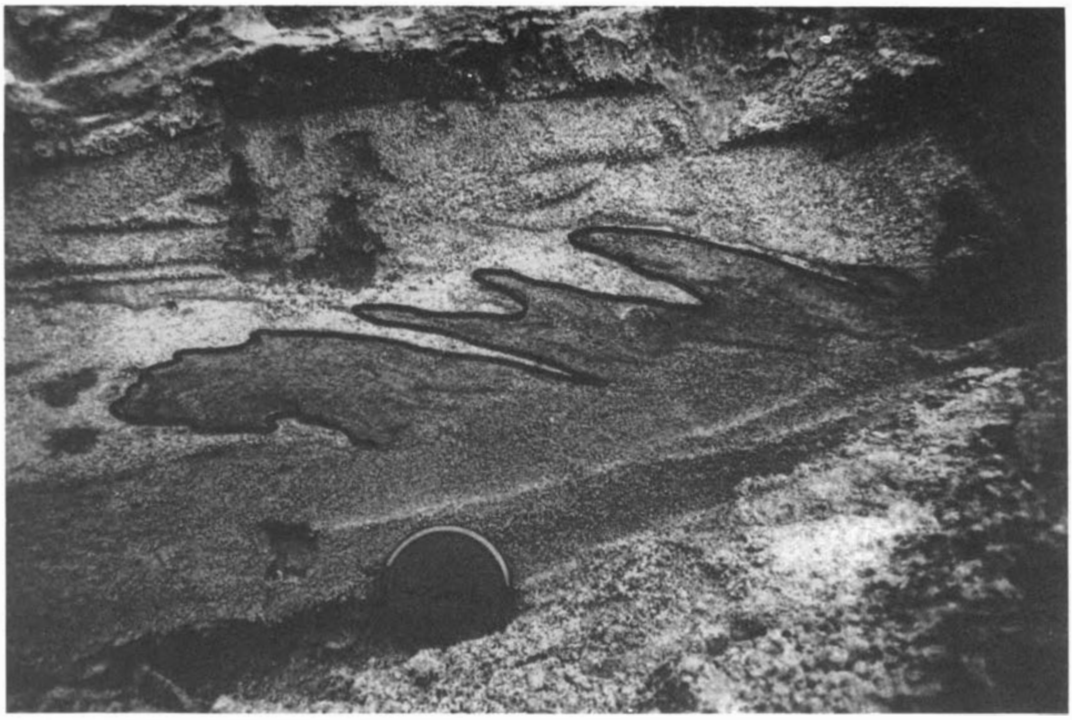

Fig. 4. Folds within bed E3 in Vistergropa resulting from a movement of the upper part from right to left.

cobbles. Isolated ice-rafted coarse gravel clasts and cobbles occur in most of the unit, and even some scattered large boulders exist. Beds below the stones are usually depressed (see Fig. 5). The foreset unit contains lenses of sandy to clayey diamicton, 0.03–1 m thick and up to 20 m wide. They are interpreted to be flow tills, and have probably flowed or slid down the slope from higher levels near the glacier front. Many subrounded to rounded, silty clay balls, 1 cm to 7 cm in diameter occur either in isolation or concentrated within distinct layers in beds D3 and D4. The balls contain ca. 40% silt and 20% clay, and they are very poorly to extremely poorly sorted ($\sigma 1$ = 3.8–4.9). Imprints of marine shells were observed in some of them. The balls must be fragments of older glaciomarine beds that were probably frozen or consolidated underneath the glacier, and later eroded and were transported with meltwater rivers. The dominating sand and gravel beds in unit D were deposited near the mouth of a subglacial meltwater stream in the same manner as the foreset beds in a Gilbert delta.

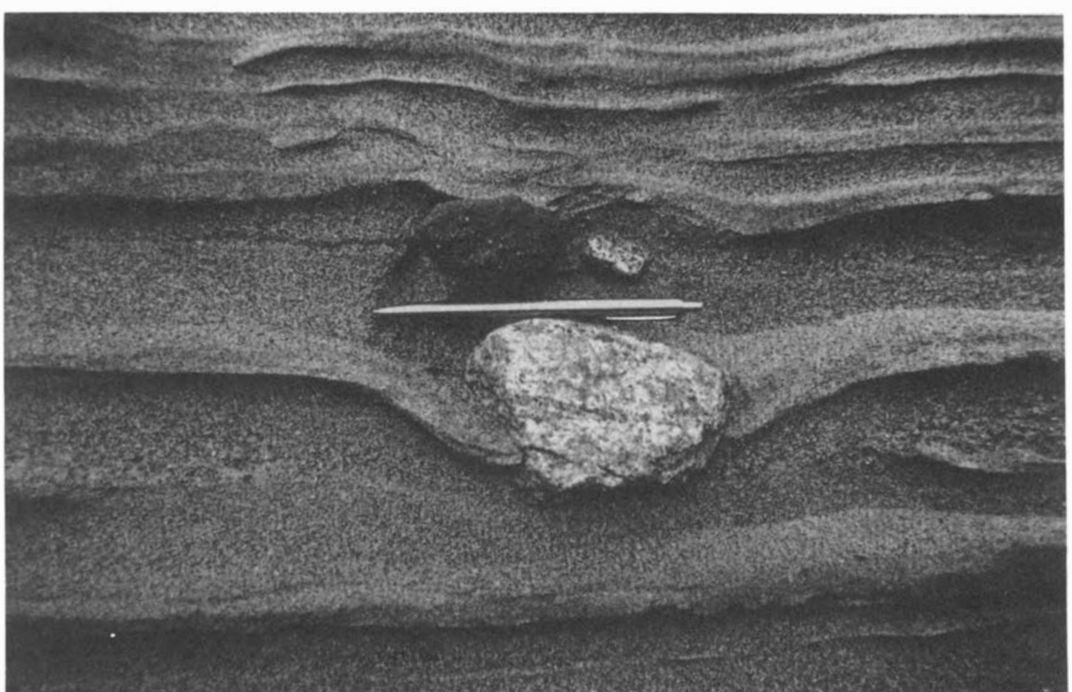

Fig. 5. Ice-dropped boulder in foreset beds at Vistergropa.

Unit C is composed of nine beds (C1–C9) (see Fig. 3a) consisting mainly of sandy diamictons (60–65% sand). The amount of clay is usually 7–8%, min. 3.5% and max. 12.1%. The diamict beds normally have erosional contacts with the underlying sediments. The sorting (for grains smaller than 32 mm) varies from about $1\sigma = 3.0$–4.0. Roundness analyses on coarse gravel show about 42% rounded and 54% subrounded to subangular grains. The nine beds in unit C are interpreted to be tills.

Bed C1 is up to 4 m thick and consists of a sandy/gravelly diamicton interbedded with thin layers (usually less than 5 cm) of gravelly sand. In the lower half of the bed there are only a few sand layers and the number increases upwards. The uppermost 0.2–0.8 m of bed C1 consists of a mixture of sandy diamicton and gravelly sand. A fabric analysis from the lower part of C1 shows two weak maxima with directions NNE–SSW and ESE–WNW (see Fig. 6). The directions are parallel with and transversal to the Ra-moraine and the regional direction of ice movement in the area, which is from NNE (Holtedahl 1960; Vorren 1977). However, the bimodal distribution may indicate that the deposition has only been slightly influenced by the ice movement or not influenced at all.

The thin sorted beds within C1 were most likely deposited in water. This could have happened in two ways: (1) The sand/gravel was deposited after free fall trough water (in water-filled chambers underneath the ice, or underneath a partly floating glacier front). The finest fractions were transported away in suspension with currents. (2) Flowing water underneath the ice eroded and reworked underlying till (Dreimanis 1969, 1979; Gibbard 1980; Åmark 1986). In this way the finest fractions were removed from the sediment.

It is very likely that bed C1 is in part a result of melt-out processes underneath the glacier front. According to Åmark (1986) melt-out processes may occur at the base of an active glacier. Combined with varying degrees of reworking by subglacial meltwater, these processes could probably explain the occurrence of the gravelly sandbeds in C1.

Beds C2–C5 are up to 3–4 m thick and dip 5–15° in a NE direction. They are all composed of a sandy diamicton, but contain lenses of sorted material probably eroded from the underlying unit D and redeposited within the tills. The distal part of bed C3 overlies beds in units D and E, with a very distinct angular unconformity dipping NE. This shows that the glacier eroded the underlying beds before the till beds were deposited by subglacial processes.

A well-defined 2.3 m-deep channel depression at the base of C5 is filled mainly with a sandy diamicton (see Fig. 3a). The channel was most likely formed as a result of subglacial erosion by meltwater and later filled with till.

Beds C6–C8 are up to 5.8 m thick and consist of sandy diamicton. In addition, C6 contains isolated fragments of tectonized sorted sediments. The fragments consist mainly of laminated, sandy and clayey sediments. Imprints of the mollusc *Macoma calcarea* were observed in one of these fragments. The fossils and the lamination show that the sediments in the fragments are deposited in a low-energy glacial marine environment. The fragments are probably eroded by the glacier and subsequently mixed with diamicton. The three beds (C6, C8 and C9) all have tongues/fingers of diamicton that wedge in between the foreset beds in unit D. Undeformed sorted beds lie below and on top of the diamicton tongues (see Fig. 7). Therefore, the tongues/fingers were deposited contemporaneously with the foreset beds and have not been squeezed in between the beds. The entire C6 bed was probably deposited by sliding and/or flowing downslope on the underlying foreset bed. The sliding could have been initiated by push from the glacier front, or just by overloading of till at the front. Bed C7, partly C8 and the proximal part of C9 overlie unit D unconformably. A very distinct discordance occurs in the area

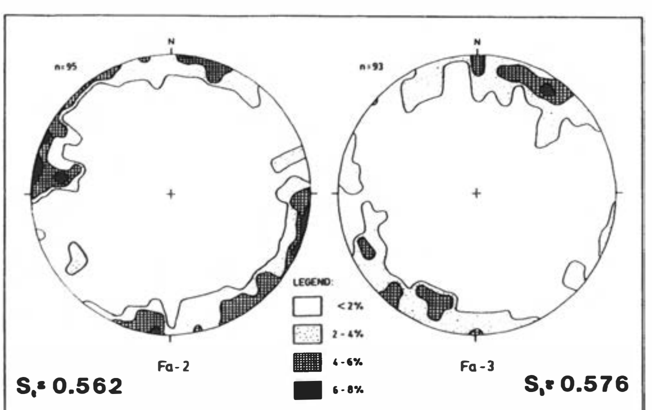

Fig. 6. Contour diagrams representing fabric analyses of two tills from Vistergropa gravel pit; Fa-2 from bed C1 and Fa-3 from bed C9. n = number of analysed stones.

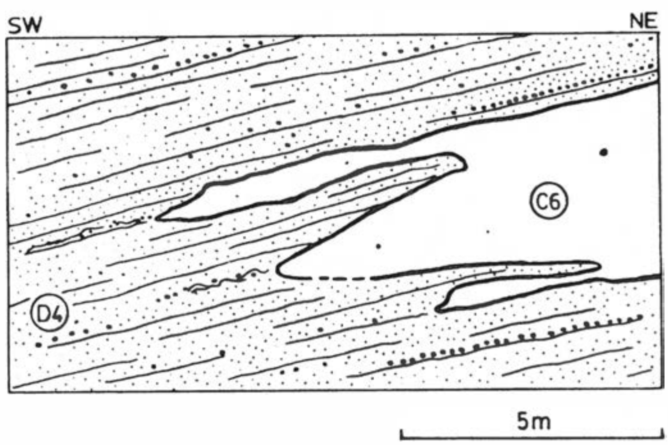

Fig. 7. Cross-section of till tongues in bed C6 between undisturbed foreset beds (D4) in Vistergropa. The tongues have resulted from flowing or slumping of the diamicton.

between C8 and C9, showing that the foreset beds were eroded before deposition of the till. Nevertheless, the tongues were deposited contemporaneously with the foreset beds. Therefore the tongues and the rest of the till units probably represent different phases of deposition.

Bed C9 is an up to 8 m-thick diamicton bed which is connected to C8 through a 0.25 m-thick diamicton layer. The bed contains several proximally dipping thin bands of sorted sediments near C8. These bands indicate that at least the proximal part of the bed was deposited below the ice front by lodgement. A fabric analysis from the upper part of the bed shows a significant orientation with a 20.5° direction and with a dip of 1.7° (NNE), (using the eigenvalue method (Mark 1973, 1974)), which agrees with the regional ice-movement direction (see Fig. 6). This supports the conclusion that the diamicton is a till deposited by lodgement processes.

Unit B occurs in small basins, where it is up to 3.5 m thick. It is composed of bedded, medium-grained sand in the lower parts, and bluish grey, poorly sorted and weakly laminated, clayey silt in the uppermost two-thirds of the unit. Isolated gravel grains were observed throughout the unit, and they are interpreted as being ice-rafted. Foraminifera or macrofossils were not found. Folds and other deformation structures occur locally in the unit, and an approximately 0.9 m wide and 0.3 m-deep channel was observed in one basin. This structure was most likely caused by a gravity flow (mudflow or high-density turbidity current). Unit B is the remains of a formerly more continuous cover of beds, which was deposited on the sea floor when the ice sheet retreated from the Ra-ridge. By comparing data from Muir Inlet, Alaska (Mackiewicz et al. 1984) with structure and grain-size data from the fine-grained parts of unit B, it was concluded that the ice front probably lay closer than 2 km from Vister when the sediments were deposited. Mackiewicz et al. found that the corresponding sediments from Muir Inlet were derived from suspensions and from turbidity currents. The basins, in which unit B occurs, protected the sediments against subsequent erosion by waves and currents.

Unit A is an up to 1.2 m-thick bed of poorly sorted gravel and sand with 10–20% cobbles and boulders. The unit is massive. It has an erosional contact at the base, which is very distinct where unit A overlies unit B. The result of a roundness analysis of coarse gravel plotted in an MR-Cr diagram (Olsen 1983) lies within the area outlined for glaciofluvial gravel, short-transported fluvial gravel and poorly mature beach gravel. Unit A was formed as a result of reworking by waves and currents of morainic deposits, mainly tills, early in postglacial time. At the same time several 1 m to 2.5 m high beach ridges, mainly of gravels and cobbles, were formed at the crest of the Ra-ridge. Because of a rapid isostatic uplift, the reworked sediments were exposed to the wave processes only for a relatively short time. Therefore the roundness of the gravel does not represent a typical beach gravel, but a poorly mature beach gravel. The poor sorting, and the fact that the reworked sediment mainly overlies tills, suggests that the till was the parent material.

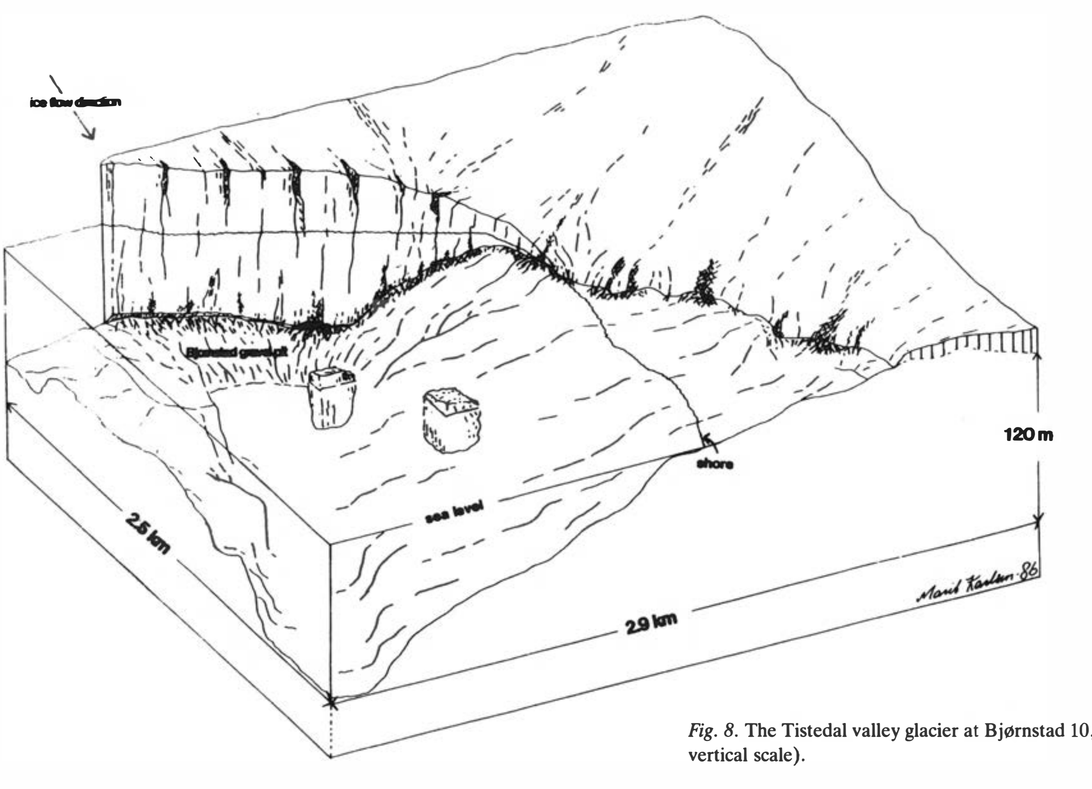

Fig. 8. The Tistedal valley glacier at Bjørnstad 10,800 years BP (6 × exaggerated vertical scale).

Bjørnstad gravel pit

Fig. 1 shows the location of Bjørnstad gravel pit (BGP) where the ice front sediments were deposited in the sea in front of the Tistedal glacier (see Fig. 8). The field work was concentrated in three sections on the pit walls. They cover the distal, central and partly the proximal part of the Ra-ridge. Fig. 9 presents a correlation of the three studied sections. Fig. 10a shows a cross-section of the Ra-ridge and Fib. 10b is a stratigraphical model. The units C–F in this model were deposited at the glacier front about 100 m below sea level, while unit A and part of unit B were deposited in shallower water during the postglacial isostatic uplift.

Unit F is 1.5–11.0 m thick and consists of cobble-boulder beds, gravel beds and sand beds which dip approximately 10°N. The unit is up to 11 m thick in the proximal parts of the ridge, not shown in Fig. 10b. A very coarse gravel with cobbles and boulders usually lies at the erosional contact with the underlying till (C2). The stones within the lower part of unit F are imbricated, with a northerly dip of 30–40°. Most of the stones are oriented with the long axis in a N–S direction, and they are mainly well rounded to subrounded. The upper 10 cm of unit F consists of laminated sand with symmetrical folds. The folds were most likely formed immediately before the overlying till was deposited.

In the eastern part of Bjørnstad gravel pit (now shown in Fig. 10b) unit F has a 10–100 cm-thick bed of laminated fine sand and clay in the lowermost part. The bed contains gravel and cobble clasts up to 10 cm in diameter. The laminae are bent downwards below the large clasts, which indicates that they are ice-dropped (see Fig. 11). Distinctive shear planes, dipping ca. 30°N, intersect the laminated unit, and folds with E–W-oriented axes exist (see Fig. 12). The shear planes and folds must have been caused by stress when the glacier deposited the upper till beds. The gravel and sand beds in unit F were deposited in subglacial rivers, which were high-energy rivers when the cobble-boulder beds were deposited. The proximally dipping beds and stone imbrication indicate that the rivers were flowing uphill under pressure underneath the glacier. This kind of subglacial uphill sediment transport

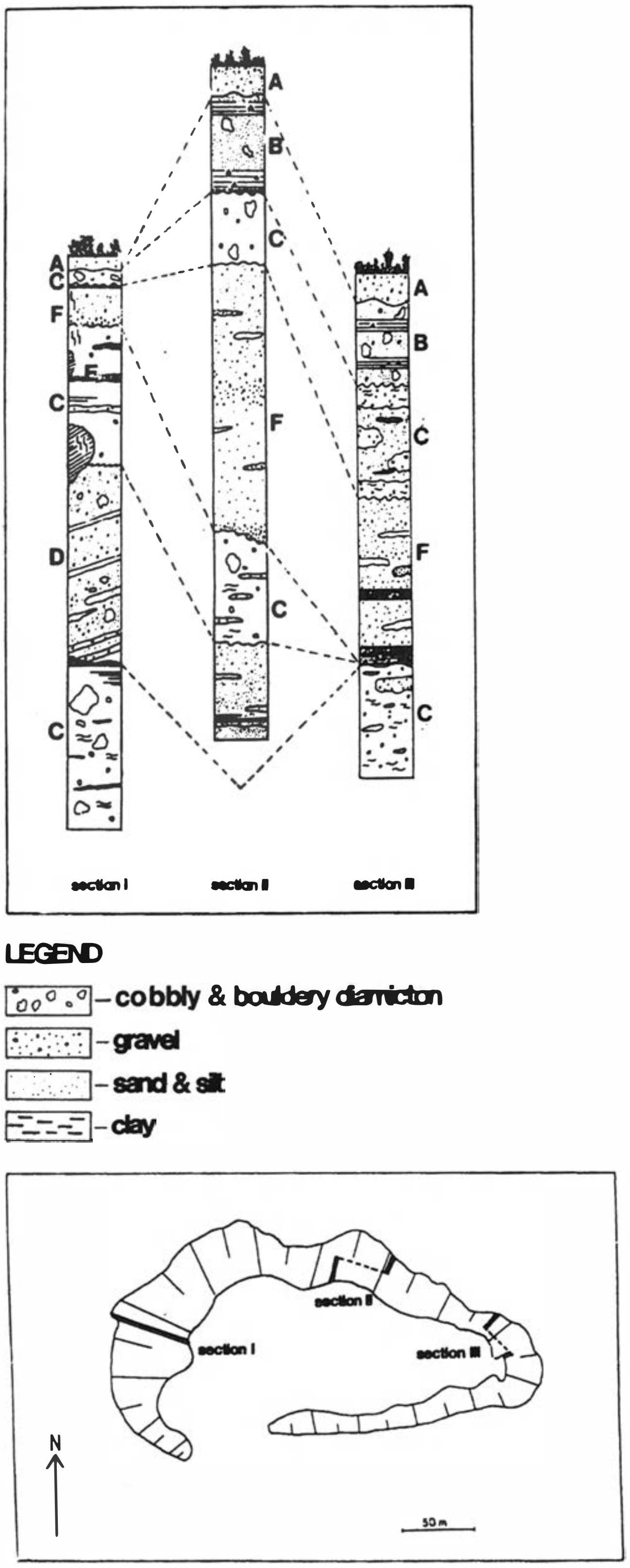

Fig. 9. Correlation of the units observed in the three studied sections at Bjørnstad. See explanation in Fig. 3a.

Fig. 10a. Cross-section through the ice-front ridge at Bjørnstad, section I in Fig. 9.

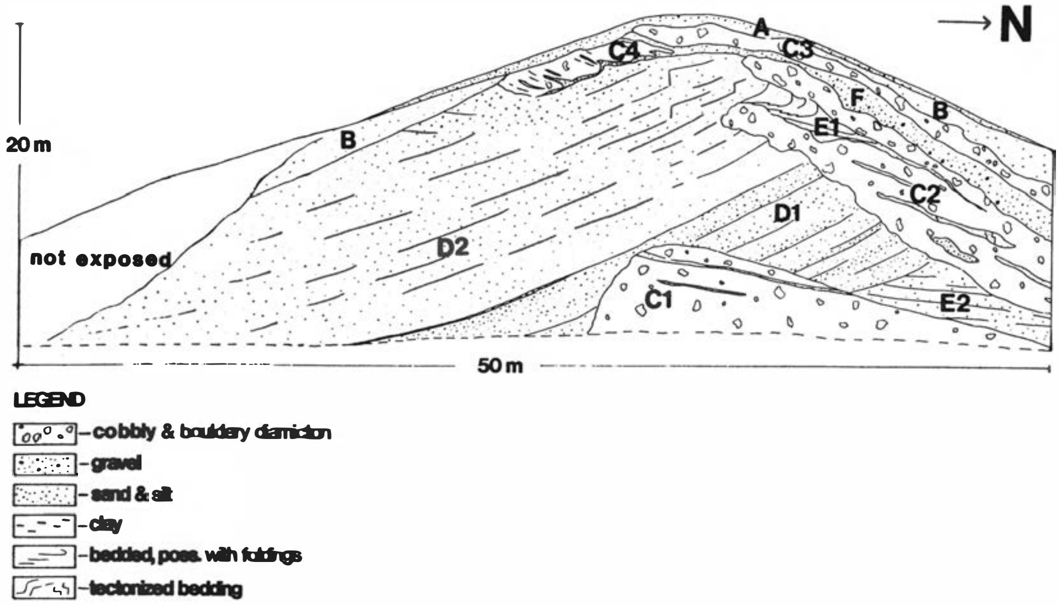

Fig. 10b. Model of the examined deposits in a cross-section of the ridge at Bjørnstad. The different units from A through F correspond with units in Fig. 3a.

near a glacier front has previously been suggested by Liestøl (1973), Holtedahl (1974) and Andersen (1979).

Unit E consists of two subunits, E1 and E2, which combined are up to 6 m thick. Subunit E1 was exposed in an unstable inaccessible part of the pit wall, which made it difficult to examine. Both subunits are composed of stratified fine sand and silt with some clay. The beds are generally horizontal, but locally they dip slightly towards the north. The subunits wedge out in a NE and SW direction. Parts of unit E1 are folded and glacially tectonized. Unit E corresponds with unit E at VGP, and the two units have the same origin.

Unit D consists of two subunits, D1 and D2, which are up to 6 m and 10 m thick respectively. Both subunits are bedded, and beds dip 15°SW. Coarse-grained sediments dominate in D1, the proximal part of the section, and finer-grained sediments dominate in D2 (see Fig. 10b). All beds are foreset beds, and many of them can be traced from the central to the distal part of the ridge.

Subunit D1 also contains beds of fine sand, generally about 5 cm thick, in alternation with beds of coarse gravel approximately 20 cm thick. The content of cobbles and boulders is 5–10% in subunit D1, while these grain sizes were not observed in subunit D2. A bed of clayey silt about 2 cm thick lies at the contact between D1 and D2. The silt bed is a glaciomarine bottomset bed.

Subunit D2 consists of medium and fine-grained sand. The dip of the sand beds decreases in distal direction, and they grade into almost horizontal bottomset beds. Unit D in BGP resembles unit D in VGP, but no tongues/fingers of till were observed between the foreset beds in BGP. This may indicate that the glacier front fluctuated

Fig. 11. Ice-dropped stone in a laminated silt and clay unit which has been faulted and folded by an overriding glacier. Unit F at Bjørnstad.

Fig. 12. Fold in unit F at Bjørnstad caused by an overriding glacier which moved towards the right.

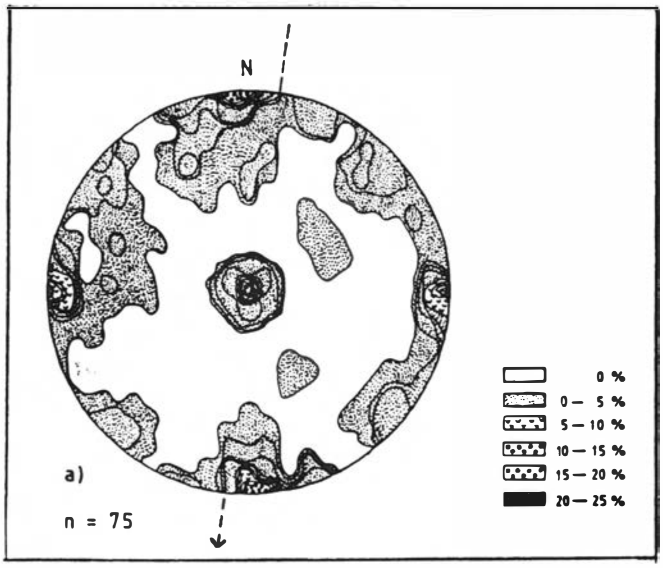

Fig. 13. Contour diagram based on fabric analysis in till bed C1 at Bjørnstad. n indicates number of stones analysed. Hatched line indicates direction of regional ice movement.

Fig. 14. Arrows mark probable shear planes in unit C1 at Bjørnstad. The planes dip in a north direction. Scale = notebook.

less during deposition of unit D in BGP than in VGP. The foreset beds were deposited at the mouth of a subglacial meltwater river in the same manner as unit D in VGP.

Unit C is a complex unit consisting of four irregular diamicton beds, C1–C4. The thicknesses of the beds vary between 0.5–2.5 m and 6 m. Grain-size analyses of the matrix conclude with a sandy diamicton with approximately 1% clay. The sorting of the matrix varies between $\sigma 1 = 1.6$ and 2.4. The content of gravel and cobbles is up to 30%, and of boulders 5–20%. Roundness analyses show a dominance of subrounded to subangular pebbles and cobbles. Based on observed textures, the erosional contact with the underlying beds and the location in an end moraine, the diamictons in unit C are interpreted as being tills. However, the tills in BGP are coarser grained than in VGP.

Bed C1 is a weakly to clearly stratified unit and relatively hard packed. A fabric analysis shows one maxima of the a-axis in a N–S direction (Fig. 13) with a secondary maxima in an E–W direction. The preferred direction is transverse to the Ra-ridge and nearly parallel with the regional direction of glacial striation in the area.

The diamicton beds in unit C1 are interbedded with 1–15 cm-thick beds and lenses of sorted sediments of mainly coarse gravel, which constitute less than 5% of the unit. The lenses of gravel and sand can be explained in different ways (see under VGP bed C1). One of the lenses in C1 is cross-laminated, and it was most likely deposited in a channel underneath the glacier. Some of the thin, slightly sorted and proximal dipping (10–15°N) beds probably represent shear planes (see Fig. 14) formed by the overriding glacier. The proximal dipping interpreted shear planes, together with an overconsolidation of the diamicton, suggests that it is a lodgement till.

A laminated 10–15 cm-thick bed of fine sand with a small amount of gravel (<5%) overlies C1. This bed may represent glaciomarine and/or glaciofluvial sediments from a phase when the glacier front was not grounded. Small lenses with sorted material in C1 may have been deposited this way, too.

Bed C2 has much the same kind of sediments as bed C1. However, C2 has a higher content of sorted beds of sand and gravel, which may indicate that the glacier front was afloat for longer periods or that the subglacial meltwater activity was higher when C2 was deposited. Several sediment lenses are tectonically deformed, which is quite normal for lenses in tills in ice-front ridges (Andersen 1979, and others). The deformation was caused by glacier-generated stress. The diamictons in C2 are most likely lodgement till, with probably melt-out processes being active during deposition. It is also possible that parts of the lodgement till are actually melt-out tills deposited when parts of the glacier front were less active or stagnant (Dreimanis 1989). According to Dreimanis (1989, p. 80) melt-out tills can occur as part of lodgement tills.

The diamictons in beds C3 and C4 have much the same character as those in bed C1, and they were therefore interpreted originally to have been deposited the same way (lodgement till). The layers in C4 dip in a proximal direction, and thrust planes and folds indicate a downslope transport of the material after deposition, which suggests slumping from higher levels of the ice-front ridge (see Fig. 15). The slumping most likely resulted from melting of the supporting ice or by melting of buried ice on the distal slope. Another possibility is that C4 is a result of glaciotectonics, and represents a tectonized distal part of C3.

Unit B (see Fig. 16) varies in thickness between 2 m and 5 m. It consists of medium to fine-grained sand and silty sand (see Fig. 10b), with 5% of the unit being isolated cobbles and boulders. The unit is partly bedded, in par-

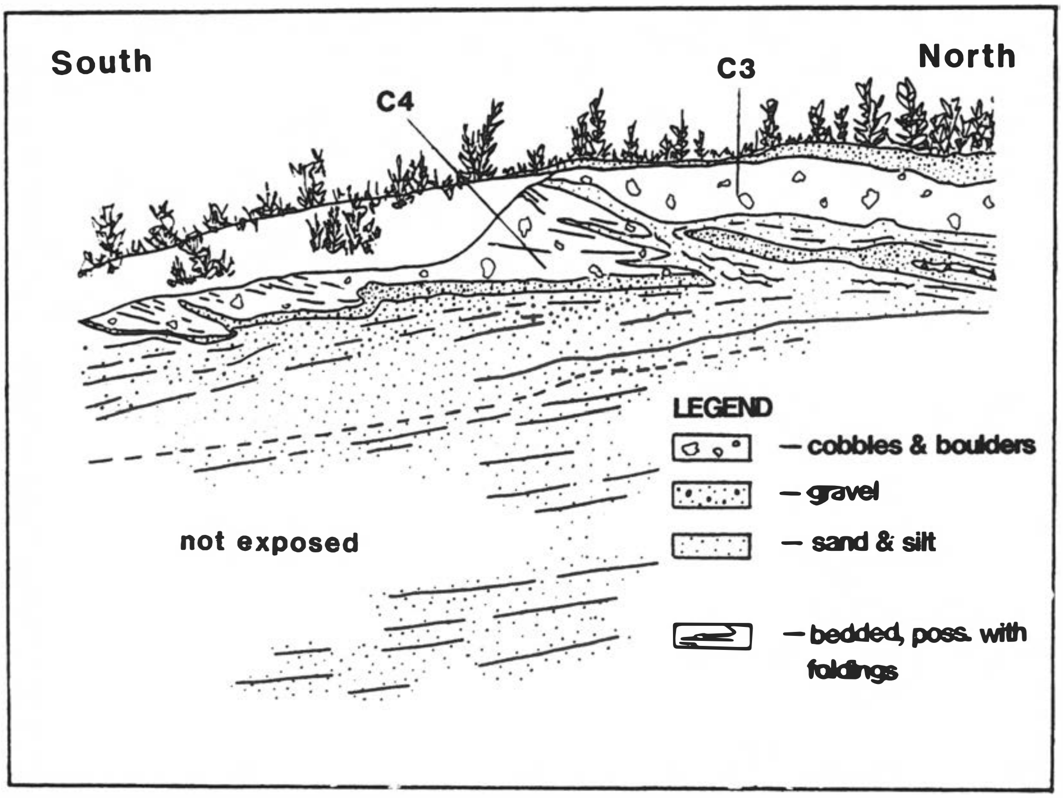

Fig. 15. The upper part of the ice-front ridge at Bjørnstad showing slumped till tongues in unit C4.

ticular in troughs or channels which are 1–3 m wide and about 0.5 m deep, and filled with medium- to fine-grained sand and silt. There the bedding is conformable with the trough floor (see Fig. 16). Unit B in BGP, like unit B in VGP, is interpreted to be glaciomarine bottomset beds, deposited when the glacier had retreated from the ice-front ridge.

The troughs or channels mentioned could have been formed by iceberg ploughing, bottom currents, or by gravity flows of downwashed sediments from the moraine or ice. Iceberg ploughing is common in front of recent glaciers, e.g. near Svalbard (Solheim & Pfirman 1985). Fossil plough marks are also very common on the shelf along the Norwegian coast (Rokoengen 1980; Lien 1983), and according to Longva (1984, 1990) they also formed in front of the Preboreal glacier in Romerike, southeast Norway. The high amount of ice-rafted boulders in unit B suggests that there was a considerable number of icebergs when unit B was deposited. Therefore iceberg ploughing is a possible cause of at least some of the observed troughs or channels.

Unit A is a 0.5–1.0 m-thick bed of mainly gravel and cobbles in a sandy matrix. The sediment is loosely packed and shows a weak, almost horizontal bedding. The stones are poorly rounded. They are less rounded than the stones in unit A at Vistergropa. However, both units comprise beach deposits formed by waves and currents in the shore zone. Grain-size analysis on matrix from unit A in BGP shows a silt content of approximately 5% and a weak bimodality. This is probably due to two different modes of deposition for the coarse and fine fractions of the matrix. The coarse fraction represents mainly a 'bedload', while the fine fraction (silt) to a large extent was derived from suspension in a low-energy environment in periods between and after deposition of the coarse grains.

Conclusions

The examined sections at Vister and Bjørnstad cross the distal and central parts of the Ra-ridge; the Bjørnstad section even crosses a proximal part. Both sections have a very similar stratigraphy, and our studies resulted in a modification of the model presented by Andersen (1979) (see Figs. 3a and 10b). The details of our model are summarized below.

Unit G consists of sand, silt and clay beds. They are glaciomarine bottomset beds deposited in an early phase before the Ra-ridge was formed. Unit H (glaciomarine clays older than the Ra-ridge) was not observed by the writers, but glaciomarine clays below unit G recorded in a core at Vister most likely represent this unit.

Unit F is composed of boulder beds to sand beds, most of which dip to about 10° in proximal direction. The imbrication of the clasts indicates a deposition by subglacial meltwater rivers which were flowing uphill under high pressure underneath the glacier front.

Unit E consists of sand, silt and clay beds and lamina. The unit is generally less than 2 m thick and lies between till beds or foreset beds. The presence of marine shell imprints and dropstones indicates that it is a glaciomarine unit which was deposited in the periods when the glacier

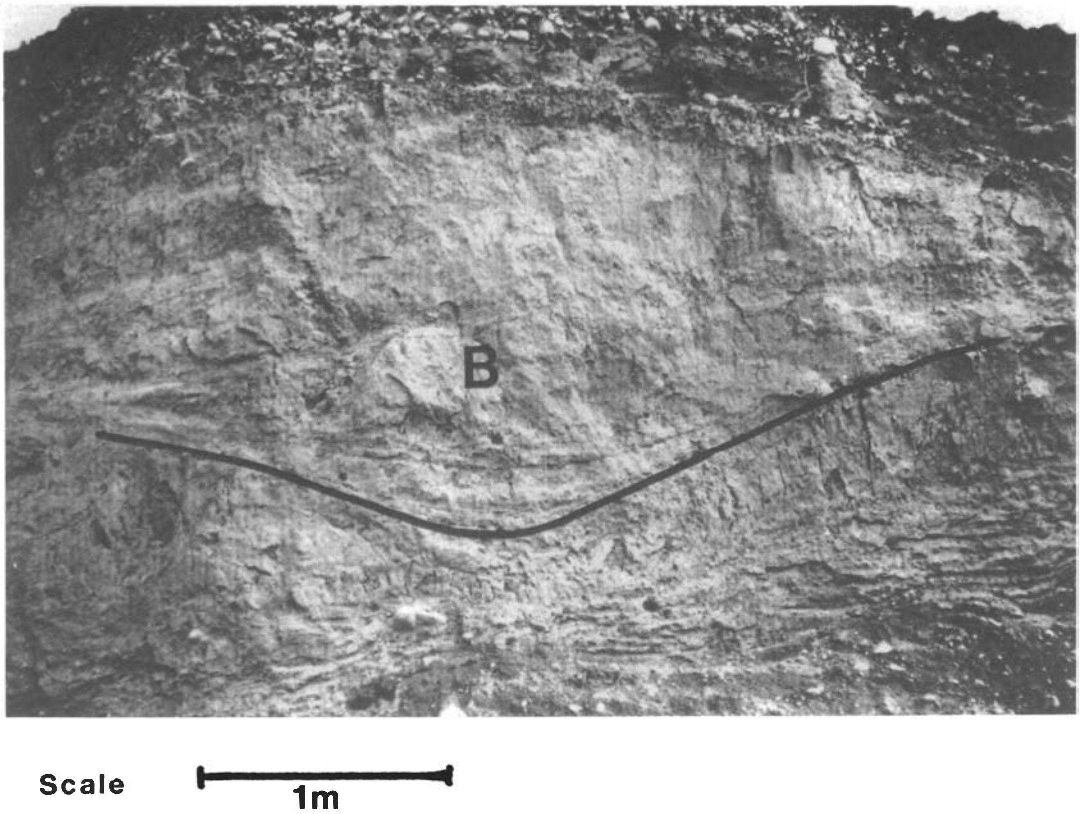

Fig. 16. Marine deposits (B) in a channel depression possibly eroded by icebergs in front of the glacier at Bjørnstad.

had temporarily retreated. Tectonized layers are either syndepositional or deformed during later glacier advances.

Unit D consists mainly of foreset beds of sand and gravel dipping 10–20° in distal direction. Lenses of till between some foreset beds represent flow or (slumped) till. The foreset beds were deposited at the mouths of subglacial meltwater streams.

Unit C consists of till beds composed of a sandy diamicton interbedded with lenses and thin layers of sorted sediments. Most of the diamictons are lodgement tills, but flow tills are also present. Melt-out processes have most likely occurred, but it is more questionable whether there are melt-out tills. The occurrence of more till beds at Vister than at Bjørnstad and the presence of more flow or slide lobes at Vister indicate that the ice front at Vister oscillated more than the front at Bjørnstad. The ice front at Bjørnstad was more protected in a narrow valley. Most of the sorted layers within the till lobes were deposited from meltwater or winnowed by water currents in a thin water layer underneath the ice front, when it was more or less floating. Several isolated, very thin, poorly sorted beds or laminae could represent shear planes. Most of them dip in proximal direction.

Unit B consists of stratified, predominantly clayey silt to silty sand, deposited as glaciomarine bottomset beds during and after the retreat of the ice front from the Ra-ridge. Shallow channels eroded in the unit could have been formed by iceberg ploughing or erosion by gravity flows.

Unit A is a bed about 1 m thick with gravel and cobble clasts in a sandy matrix, formed by reworking of till and glaciofluvial sediments by shore and nearshore processes when the Ra-ridge passed sea level. The clasts are less rounded than in typical beach deposits because of a rapid isostatic uplift. Distinctive beach ridges were formed on the crest of the Ra-ridge which was most exposed to wave activity.

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