Flood deposits in the Hornelen Basin, west Norway (Old Red Sandstone)

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Breccias, conglomerates, and sandstones of the Hornelen Basin were deposited as alluvial fan and slope sediments in a tectonic valley which dipped westwards from highlands in the east and southeast. The rocks display various scales of rhythmic sedimentation.

Minor rhythms (up to a few metres thick) are characterized by one or more of these lithofacies in upward succession: basal pebbles (A), massive sandstone (B), parallel laminated sandstone (C), cross-bedded sandstone (D) and cross-laminated sandstone (E). Each such sedimentary unit is bounded by a thin siltstone interval or by an erosional surface where the top is truncated. These minor rhythms can be related to flood deposition in uniform or decreasing flow-regimes.

Megarhythms (usually from a few metres up to hundreds of metres thick) often coarsen upwards. They can be related to progradation of fans and valley floor alluvial wedges in response to levée breaching following pulses along the original fault-bounded escarpments.

Very fine sandstones which occur in the finer part of the sandstone megarhythms and close to the margins of the basin are probably related to overbank flooding or flooding on distal parts of the alluvial slopes rather than to deposition in permanent lakes.

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The rhythmic alternations between finer and coarser sandstones in Old Red Sandstone of the Hornelen Basin district (Kolderup 1927) have been attributed to deposition in wandering river channels influenced by pulsatory tectonic activity along the basin's marginal faults (Bryhni 1964 a, b). Sands in the axial part of the basin were deposited by generally westward-directed currents, while marginal fanglomerates originated as flows of 'talus' down the scarps of active faults. Recent accounts of Old Red Sandstone sedimentation in western Norway have emphasized the significance of alluvial fan and braided stream environments during deposition (Nilsen 1973, Bryhni 1975a, Steel 1976). More recent work by colleagues at Universitet i Bergen has been published immediately after delivery of this manuscript. An important contribution is Steel, R. J., Mæhle, S., Nilsen, H., Røe, S. L. & Spinnangr, Å. (1977).

In the Hornelen district a thick succession dips generally eastwards along the middle part of the basin (Fig. 1). Normal faults and bedding plane faults have probably contributed to the enormous apparent thickness (~20,000 m) revealed in the longitudinal profile. The succession rests with angular unconformity on assumed Lower Paleozoic and older rocks in the west and is cut by faults at the northern and southern boundaries. A sole thrust transects the sequence on the eastern margin and probably underlies most of the Devonian rocks. The observed succession only represents a portion of the original basin, as it is truncated by the sole thrust to the east and by the present erosional surface to the west.

A rock stratigraphy can be best defined at the western margin where five units are mappable on a regional scale (Fig. 2). In the neighbouring Bulandet-Værlandet district, Nilsen (1969) designated the units recognized there as 'Members' of the Bulandet-Værlandet 'Formation'. I prefer, however, to follow Skjerlie (1971) in reserving the 'Group' designation for the Old Red Sandstone rocks within each district and define 'Formations' by their lithology. 'Formations', so defined, may intertongue with each other like the Tertiary Wasatch and Green River Formations in the Rocky Mountains region (Bradley 1964). A simple stratigraphic scheme for the island of Batalden in the westernmost part of the district is:

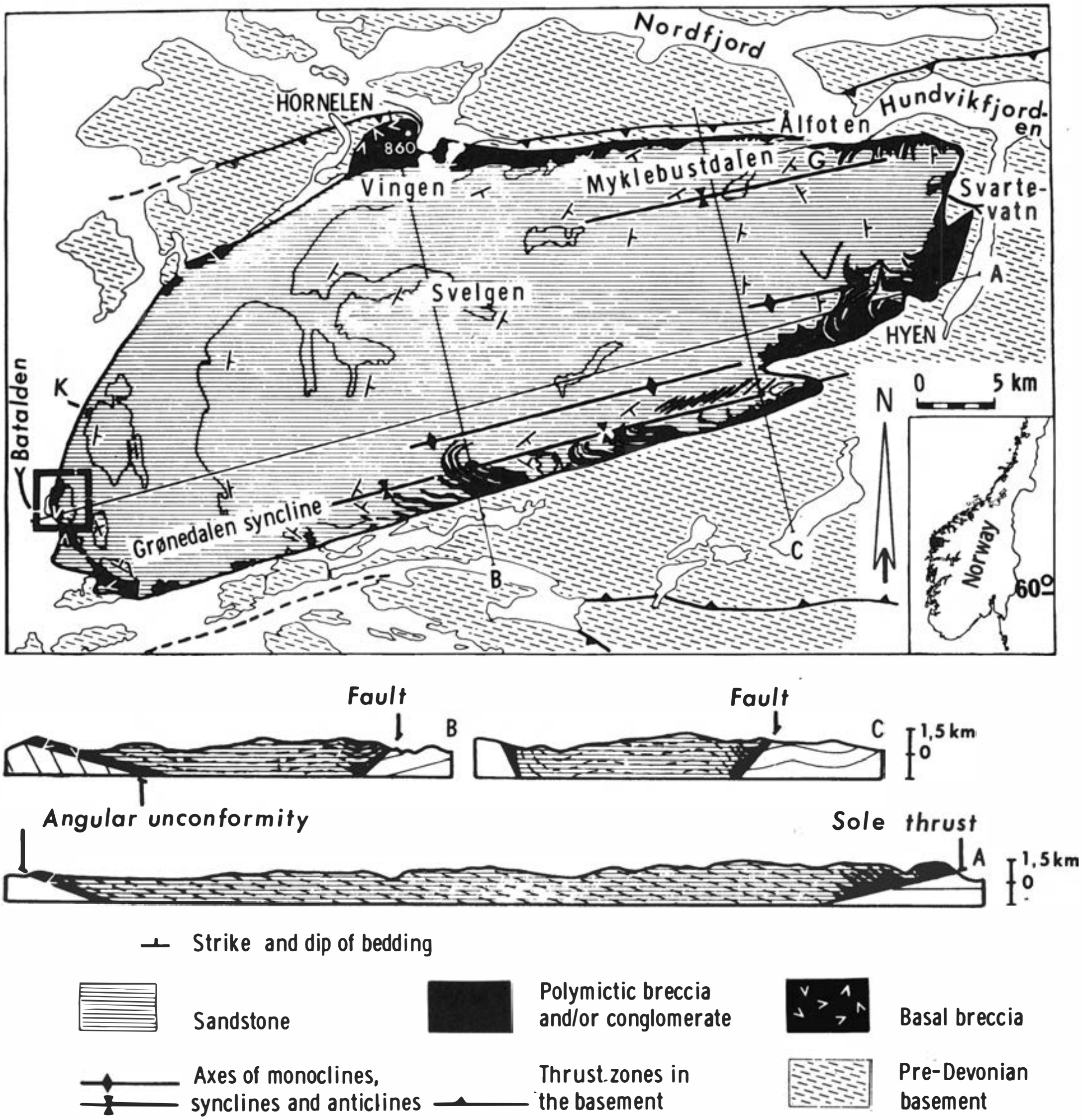


Fig. 1. General geology of the Hornelen Basin. The mountain Hornelen is indicated with a white dot and its height 860 (metres a.s.l.). Area within the heavy square is shown in more detail in Fig. 2. K: Kvannhovden, G: Gjegnalund.

Hornelen Group	Formation V:	Green sandstone
	Formation IV:	Polymictic conglomerate
	Formation III:	Green and red, very fine sandstone and siltstone
	Formation II:	Polymictic breccia
	Formation I:	Basal breccia with red sand- and siltstone

Unconformity ____________________

Formation I of Batalden (Fig. 2) is only developed in depressions in the Pre-Devonian basement, while Formation II (well developed at Tjeldnes) continues to the fault-bounded northern and southern margins of the basin where it intertongues with sandstone. Formation III (well developed at Rindevikja) has a regional distribution and is significant because it might indicate local ponding at the onset of the westward-directed alluvial deposition in the district. Formation IV is transgressive and erosional on the

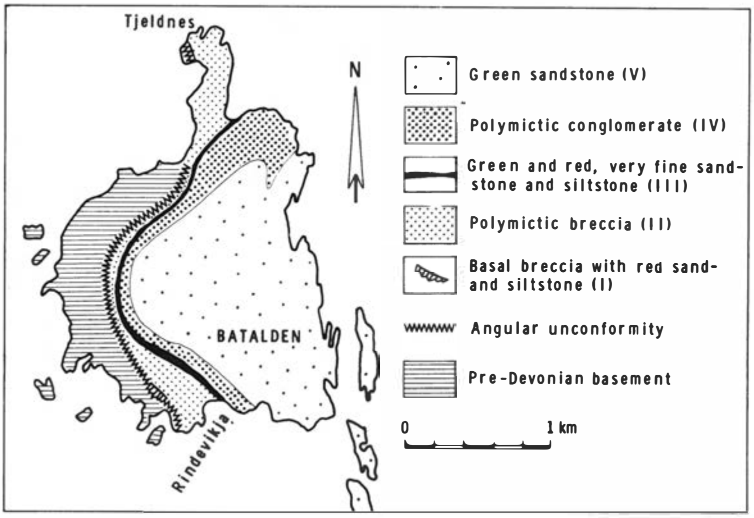


Fig. 2. Geology of the island of Batalden, westernmost part of the Hornelen Basin (for location see Fig. 1).

underlying fine-grained sediments. Interstratified sandstones increase in abundance upsection and are similar to those of the overlying Formation V.

Sandstones of Formation V are indistinguishable from those which make up the major part of the Hornelen Basin and which intertongue into breccia and/or conglomerate at the basin's margins (Fig. 3). The interfingering of sandstone with breccia or conglomerate usually displays various scales of rhythmic alternations between finer and coarser sediments. *Megarhythms* involve many sedimentation units and are usually several tens or maximum 100–200 metres thick (Bryhni 1975, Steel 1976), while *minor rhythms* are restricted to individual beds or sedimentation units. The megarhythms are often expressed topographically by ridges where the top is in the upper part of the coarser interval.

The present contribution gives some of the background material for previous conclusions (Bryhni 1975a) about coarsening-upward rhythms being 'related to tectonic movements along the basin margins' and 'westward aggrading coarse channel material over the floodplain successions'. The description here, whenever possible, is separated from the interpretation, because some of the interferences may still be controversial (cf. Bryhni 1975b). Most of the conclusions on coarsening-upward rhythms are, however, in agreement with those of Steel (1976).

Fanglomerate rhythms

The sediments along the margin of the basin are often coarse poorly sorted rudites, with angular fragments and indistinct matrix. These sedimentary breccias often grade rapidly both laterally and vertically into conglomerates with rounded clasts. The term 'breccia' will therefore be used here to emphasize the angularity of the clasts in certain varieties of the fanglomerates.

Sequences near the base of the succession

Three coarsening-upward megarhythms, with breccias containing fragments of essentially angular gneiss, can be distinguished above a residual greenschist breccia on the Hornelen mountain near the northwestern margin of the basin (Fig. 4). The sediments here are probably equivalent to breccias of Formation II on Batalden. The megarhythms are up to ~200 m thick and are separated by a few metres of interbedded conglomerate and parallel-laminated, channelled, and cross-bedded sandstone. The more massive breccias immediately above the relatively fine sediments have mostly granule-sized clasts, but cobble to boulder-sized inclusions, coarser interbeds, and many erosional remnants of sandstone a few centimetres thick can be found. The distinct bedding in the basal part of the rhythms gives way upwards to a massive breccia with clast diameters sometimes

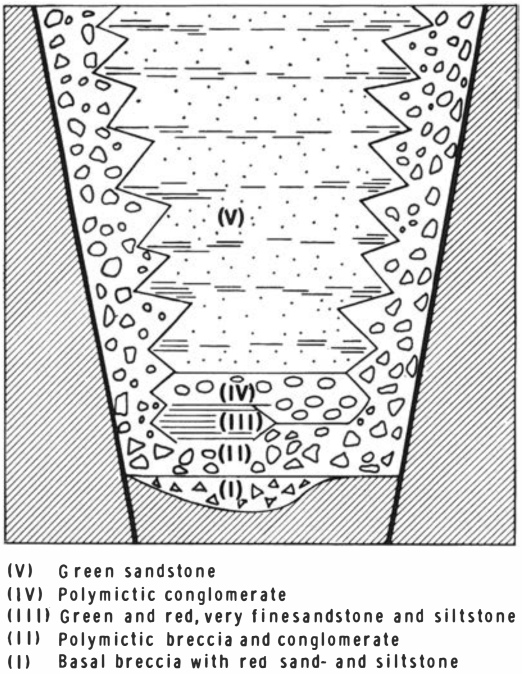


Fig. 3. Schematic NS profile through the Hornelen Basin (not to scale), based on the westernmost area.

in excess of a metre and no discernible fine-grained matrix. Bedding in this massive breccia is locally defined by ledges caused by differential weathering, by vertical variation of clast sizes, by flat clast alignment, by trains of imbricated clasts, or more rarely by normal graded beds 1–2 metres thick. Elongated clasts are aligned NW–SE, almost in accordance with unimodal SSE directed palaeocurrents deduced from trough axes in overlying sandstones outcropping along the fjord (Fig. 5).

A bed of breccia (unit 5 in Fig. 4), up to 10 m thick and exposed laterally for about 50 metres, occurs below the upper, approximately 200 m thick megarhythm on the mountain Hornelen. It is essentially composed of clasts of amphibolitized gabbro, quartz schist, and trondhjemite of assumed Lower Paleozoic age, and thus differs strongly from adjacent breccias which have Precambrian gneiss as the dominant clast lithotype. The upper and lower contacts of the beds are planar without evident erosional features. This exotic breccia has monomictic domains, at places with only gabbroic clasts, and contains the largest boulders yet found within the Hornelen Basin. A trondhjemitic boulder has

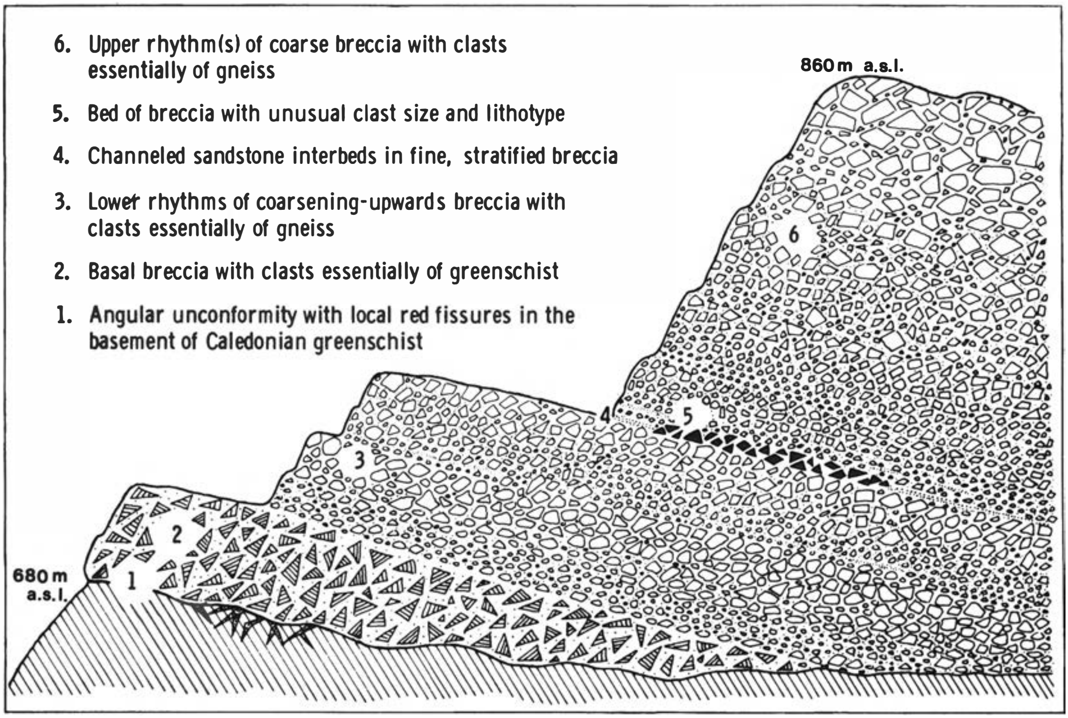


Fig. 4. Schematic section through the mountain Hornelen (not to scale).

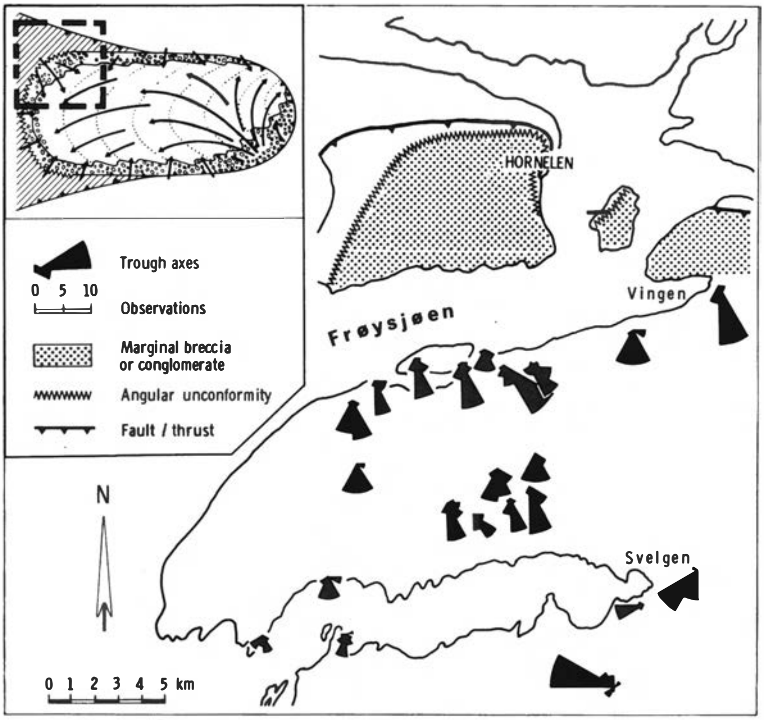


Fig. 5. Palaeocurrents in sandstones (rose diagrams) directed away from the area of breccias in the mountain Hornelen (stippled area). Diagrams are based on trough cross-bedding azumuths rotated on bedding strike to horizontal. Inset: 'Generalized basin' of Old Red Sandstone in western Norway, with arrows indicative of palaeocurrent directions (from Bryhni 1975a).

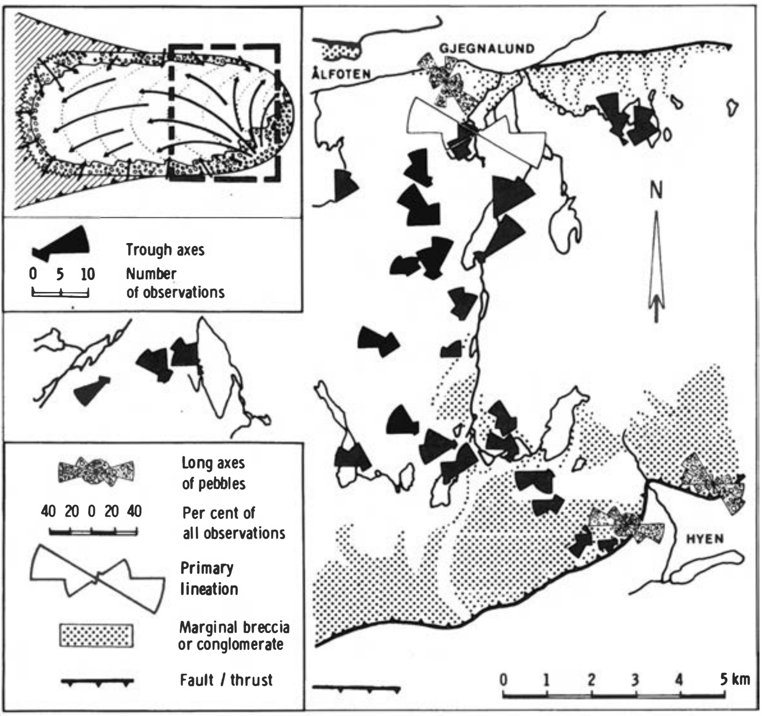


Fig. 6. Interdigitation of marginal breccias or conglomerates into sandstone in the eastern part of the basin. Palaeocurrents in sandstone are directed away from the area of breccia near Hyen, the detritus almost reaching the northern margin. Diagrams and inset as in Fig. 5.

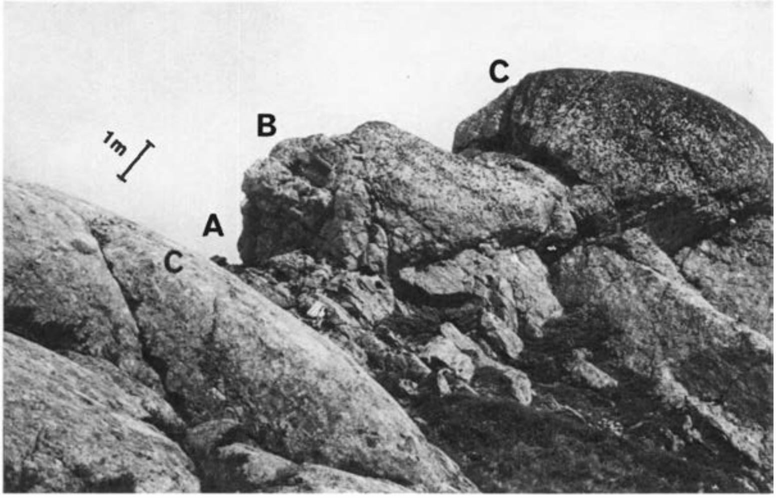


Fig. 7. Coarsening-upward rhythm, northern margin of the Hornelen Basin, SE of Metnes (upper part of Profile 2 in Fig. 8). A: Sandstone, B: Stratified breccia or conglomerate, C: Rather massive breccia or conglomerate.

exposed dimensions of 2.5 × 2 metres, while a boulder of banded red-black quartz schist measures 1.5 × 1.5 metres. Sandstone with contorted bedding occurs between some clasts but there is usually no distinct matrix nor internal stratification within the bed.

Interpretation

The megarhythms above the residual breccias on the mountain Hornelen can be interpreted as products of a succession of three alluvial fans. They prograded southeastwards into the basin over a disconformable surface eroded in the Lower Paleozoic schists and intrusive rocks, and were fed from a highland area composed essentially of Precambrian gneisses. Deposition was mainly from sheets of running water but massive breccias, and particularly the exotic breccia below the upper megarhythm indicate that debris flow deposits also contributed to building up of the fans.

More detailed discussion will be postponed until the other sequences along the basin margins have been described.

Sequences along the margins

The part of the basin that has been preserved is rather asymmetric since detritus from the southeastern margin appears to have been transported almost to the northern contact (Fig. 6). This relationship was shown in the 'Generalized basin' of Bryhni (1975a) which was made mainly on basis of data from the Hornelen district, but the dispersal pattern differs in this detail from that given by Steel (1976).

Coarsening-upward rhythms were figured in Bryhni (1975a) and described in more detail by Steel (1976). The present study adds some more data from the northern margin in the eastern part of the basin. Deposits derived from northern and southeastern sources can be distinguished in this area by their dominant dioritic or quartzitic clast lithotypes respectively.

A typical coarsening-upward rhythm starts with an interval of sandstone/siltstone (A) which is overlain first by stratified breccia or interbedded breccia/sandstone (B) and ends with coarse, indistinctly stratified or almost massive breccia (C) (Figs. 7 and 8).

The normal sequence ABC–ABC is developed in areas where sandstone occurs in substantial amounts, while BC–BC or C–C occur in areas with dominant breccia. The thickness of the rhythms is only 0.5–2 metres in the lower part of the ridges but attain several tens of metres thickness in the higher part of ridges. The thickness of individual lithofacies types is strongly dependent on the location in the basin; thick single breccia units (up to 80 metres in the profile) are only developed close to the margin which now is a fault. A series of individual rhythms may fine upwards or, more commonly, coarsen upwards and thus form megarhythms of higher order.

The lithofacies A, B, and C will be described with reference to three measured profiles in the

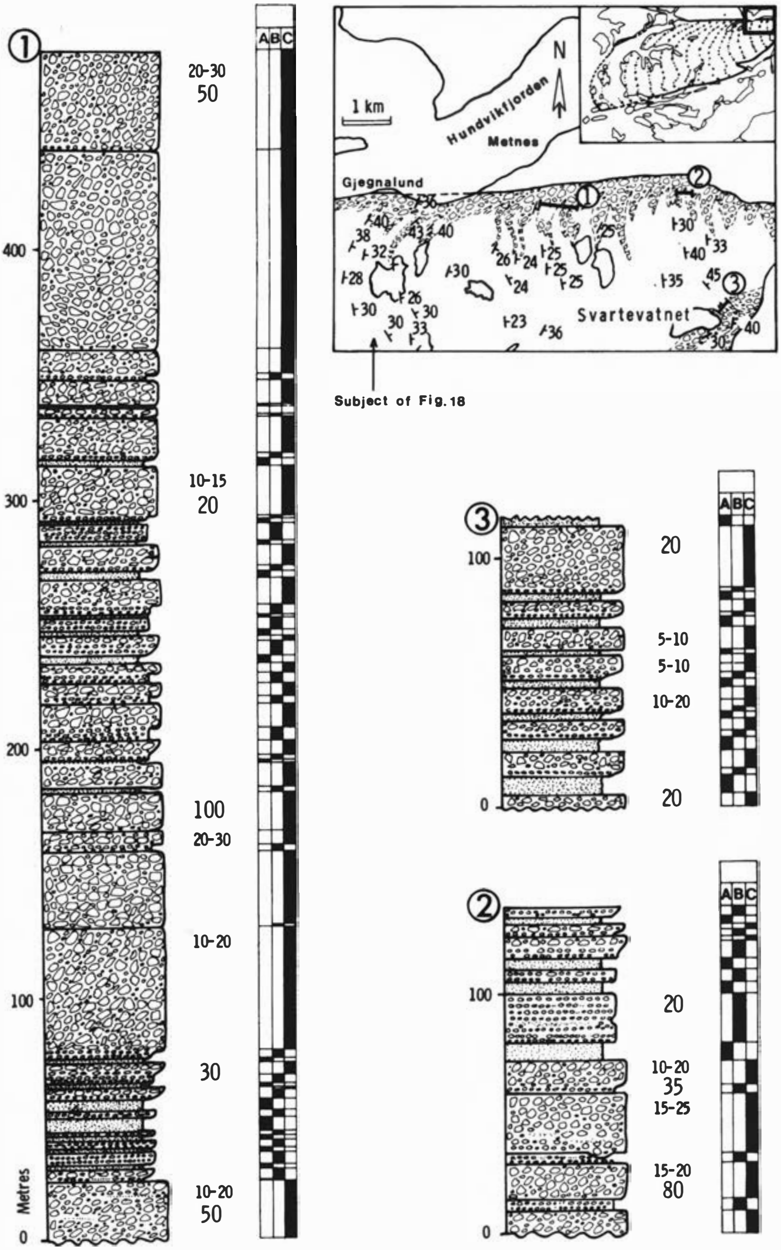


Fig. 8. Lithofacies profiles from the northeastern margin of the Hornelen Basin (localization indicated on inset). To the right of each column the larger numbers give the maximum and the smaller numbers the average clast long-axis (in cm). Lithofacies A, B and C are referred to on pp. 278–280.

Svartevatnet–Metnes area (Fig. 8) where the clasts are dominantly dioritic and thus differ from those in the laterally equivalent sandstones.

A. Essentially sandstone, with interbedded fine breccia and siltstone, occurs at the base of the megarhythms and decreases rapidly in thickness towards the basin boundaries. Lamination in the lowermost part of these units clearly indicate that sand- and siltstone infill hollows in the upper surface of the subjacent breccia. Dominant structures are parallel lamination, cross-lamination and cross-bedding. The coarse beds often have channelled bases, mud cracks occur on the top of fine-grained sandy and silty beds, inclusions of large clasts are common and calcareous concretions are occasionally present in the sandstone. Fine corrugations, here interpreted as wrinkle marks, have been noted on the top of a few silty beds.

Dioritic clasts similar to those seen in the almost monomictic breccias of lithofacies B and C dominate the breccias of facies A, but gneiss, quartzite, and vein quartz clasts also occur. A few measured foresets in a cross-laminated sandstone above a massive breccia at Svartevatn indicate deposition by currents flowing to the ENE as in the laterally equivalent thick sandstone sequences; – a transport direction which is quite different from that of the associated breccia.

B. Essentially stratified breccia, occurs in coarsening-upward sequences of interbedded coarse sandstone and breccia. The lower contact with sandstones of facies A is usually marked by the much higher proportion of coarse (granule to pebble size) material in the overlying unit, the base of which is either flat or channelled. The following features are common within this interval: gradational transitions between individual beds, inclusions of larger clasts, couplets with breccia at the bottom and sandstone at the top, normal grading, channelling below coarse beds, flatly truncated cross-beds, parallel lamination and cross-lamination. The combined thickness of breccia-sandstone couplets usually range from a few centimetres to several tens of centimetres; the frequency, thickness and exposed lateral extent of the erosional remnants of sandstone decrease upwards.

Clasts within the three measured profiles are essentially composed of diorite and similar rocks, but quartzite and other metamorphic rocks do occur, especially in the sandstone interbeds.

C. Rather massive breccia or conglomerate occurs in units which range in thickness from less than one metre to 80 metres. The top is often marked by an extensive planar surface which forms the upper ledge of the ridges.

The beds of profile 1 and 2 on Fig. 8 have sometimes channelled bases (up to >1 m deep). Thin and not very extensive erosional remnants of sandstone occur especially in the lower part of the intervals and suggest individual breccia bed thicknesses in the order of 0.2–2 m. The clasts are significantly rounded and increase in size upwards to the top of the ridge-forming units where largest clast diameters often exceed a metre. There are few sandstone interbeds or erosional remnants in these massive rocks and a consistent NW–SE alignment of boulders can often be seen. Diorites and related plutonic rocks dominate among the clasts. The most common clast lithotypes are gabbro, diorite, quartz diorite, augen gneiss or other gneisses, and rarely quartzite.

The breccia has a framework structure with little unsorted matrix between the clasts. Well-sorted sandy fillings of voids between the clasts can be seen at places.

Stratified breccias with deep channelling below and occasional normal grading within individual beds (Bryhni 1964b) also occur in this interval.

The breccias of profile 3 on Fig. 8 are quite massive without any sandy interbeds. Individual units have flat tops and terminate abruptly when traced laterally. Many of the units have >98% dioritic clasts and could almost be mistaken for some igneous rock, while other units have only about 90% dioritic and 10% quartzitic and amphibolitic clasts.

A sample of almost monomictic diorite breccia (Fig. 9) has randomly angular or slightly rounded clasts without distinct matrix, the larger clasts being set in a mass of smaller fragments. Red limonitized spots occur in the clasts, and carbonate can be identified in domains with much fine material. The top of the massive breccia has well-rounded cobbles or boulders draped by the lowermost bed of facies A sandstone. Clast elongation in this top layer of the breccia is between E–W and SE–NW, quite different from the palaeocurrents suggested by trough cross-lamination in the adjacent sandstones.

Linear bodies of breccia along the southern margin have an en échelon distribution in the sandstone, a feature which is well displayed in the Grønedalen syncline (Fig. 10). Coarsening-upward rhythms with abrupt lateral termination can be seen in some of the individual breccia units. The pre-folding direction of these linear bodies was NE–SW, parallel to the NE current directions deduced from trough cross-bedding in sandstones close to the southern margin. Coarse beds in interbedded sandstone-conglomerate sequences along this margin often display normal grading.

The relations seen in Fig. 10 indicate that the locus of sedimentation moved eastwards during deposition (Bryhni 1964 a).

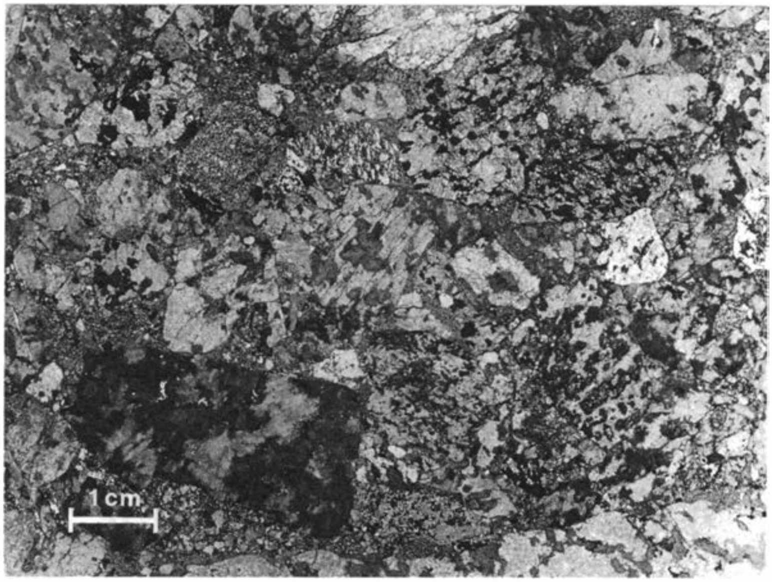


Fig. 9. Thin-section of diorite breccia, Svartevatnet.

Interpretation

Depositional agents on modern alluvial fans are sheetfloods, streamfloods, debris flows, and mudflows (Davis 1938, Blissenbach 1954, Bull 1972). In addition, sieve deposits (Hooke 1967) are formed where surfacial fan material is so coarse and permeable that even large discharges infiltrate completely into the fan before reaching its toe. Many compound alluvial fans extend from a mountain front to a floodplain where rivers rework the fan material and influence its base level (Blissenbach 1954).

The fault scarps originally bordering the Hornelen Basin to the north and south were probably located near to the present margins, as tongues of coarse clastics extend up to 4 kms from the present boundaries. The general basis for this inference is the presence of coarse proximal rubble, cobbles, and boulders grading basinwards into distal sands.

The sandstone intercalations between conglomerates (lithofacies A) are due to three possible processes:

aeolian activity,

alluvial deposition of fine material derived from the same source as the coarse clastics or

alluvial deposition on the distal end of a second, overlapping fan or from alluvium of the valley floor.

Mud cracks and possibly also wrinkle marks in the sandstone interbeds indicate intermittent emergence during deposition, but there is no evidence of aeolian deposits. The other two possible processes are, however, both realized, and can be distinguished in certain areas.

Distal sandstones from the mountain Hornelen alluvial fans appear to be overlapped by valley floor sandstones deposited by westsouthwest flowing river systems in the Svelgen area (Fig. 5), but interpretation is here complicated by the different stratigraphic position of the beds in which the various palaeocurrents were measured. The situation is more clear at Hyen (Fig. 6), where a more restricted fraction of the succession can be studied. Larger fans from the southeastern margin appear here to have extended across the basin to the present northern boundary, where their distal ends interfingered with fans from the northern margin. The higher proportion of quartzitic clasts in the sandstone lithofacies north of Svartevatn (Profile 3, Fig. 8) indicates that the sands were derived from a different source to that of the dioritic clast-dominated coarser material with which they are interbedded. A likely explanation is that lithofacies A most commonly belongs to the valley floor alluvium while B and C belong to the alluvial fans which prograded basinwards across the northern fault excarpment.

The sandstone intercalations between thick breccia or conglomerate sequences are products of deposition in the upper part of the lower-flow-regime (cross-beds) and in the upper-flow-regime (parallel-laminated beds). Trains of imbricated clasts and normal grading indicate that the stratified to massive beds higher up in the sequences were also deposited by running water. Deposition was probably by braided streams succeeded by progressively more sheetflood up-section.

The exotic breccia in the lower sandstone interval below the mountain Hornelen requires further comments at this stage. It has clasts derived from the Lower Paleozoic part of the basement while the adjacent gneiss breccia is made up essentially of Precambrian detritus.

The bed could be a residual breccia brought into its present position by bedding plane faulting, but evidence of such tectonic repetition has not been observed. A more likely explanation is that the exotic breccia is a debris flow deposit (Fisher 1971, Bull 1972) at a relatively mature stage of fan development. The concentration of gabbroic clasts into domains of almost monomictic breccia containing very large boulders indicates that the debris flow may have been derived from a terrain which otherwise did not provide much detritus. It may have been initiated by a large rock fall thus representing a *sturzstrom* in the sense of Hsü (1975). The massive conglomerates in the higher part of the megarhythms at the mountain Hornelen probably represent increasing debris flow deposition from an essentially gneissose source, north of the fault shown in the upper left part of Fig. 5.

Normal and inverse grading appear to be common in rocks interpreted as alluvial fan deposits (Nilsen 1968, McGowen & Groat 1971), and both types are also common in lithofacies B and C of the fanglomerates of the Hornelen Basin. Stratification within lithofacies B indicates deposition as longitudinal bars in shallow braided streams while less frequent cross-bedding may be related to transverse bars and dunes. Downcurrent progradation of bars with the upper, coarsest clasts facing the stream can have produced some of the inversely graded beds or sequences. However, the general coarsening-upward pattern of most megarhythms must be related to deposition in successively higher stream energies. Individual couplets in lithofacies B were probably deposited under single flood episodes. Channelled sandstone interbeds in the lithofacies C testify that the channels were entrenched at places (streamflood), but the majority of the coarse breccias in the upper part of the rhythms occur in flat, extensive units with only shallow scouring at their bases. A possible analogy can be sought in the sheetfloods which occur when an exceedingly large amount of water and detritus emerge from a mountain canyon and spread out on alluvial fans in the form of a sheet (Davis 1938, Blissenbach 1954, Bull 1972). The normal graded beds were probably deposited under flood surges with decreasing discharge of water. Sandstone interbeds or erosional remnants in lithofacies C may have been deposited as a cover on the coarser pebble/boulder sheet in the waning stages of the floods. The distinct break which often occurs at the top of the coarser beds indicates, however, that the sandstone interbeds in breccia were related to minor settling in gullies subsequent to deposition of the coarse sheets.

Streamflood and sheetflood processes were probably the dominant depositional mechanisms also along the southern margin. The linear bodies seen in Fig. 10 possibly represent deposition by spasmodic floods confined to wide channels or washes in fans made up essentially of braided-river/alluvial slope sandstones.

The massive diorite breccias of lithofacies C in the Svartevatn area have no internal structures which indicate deposition by running water, but are similar to monomictic domains in the exotic breccia from the mountain Hornelen. The massive, internal structure, plane bases without evidence of significant erosion of subjacent beds, coarsening-upward sequences within individual units, poor sorting, and lateral abrupt contact against sandstones suggest deposition by debris flows (Hooke 1967, Johnston 1970, Fisher 1971, Bull 1972). The contents of fines in these rocks are low; estimation of the thin section illustrated in Fig. 9 indicates that only about 2% of the rock is of sand grade or finer. This content of fines is believed sufficient, however, for the debris mass to flow (see Curry 1966:773). The fluid pore pressure at the base of a wet debris mass may have been considerable for short intervals and to some extent carried the weight of the overburden. Thus the friction opposed to flow may have been significantly reduced.

It is probably impossible, in most cases, to classify any individual bed as a streamflood or debris flow deposit. Even in 'simple' cases of rubble beds deposited by flood surges related to the breakdown of artificial dams, it is difficult to

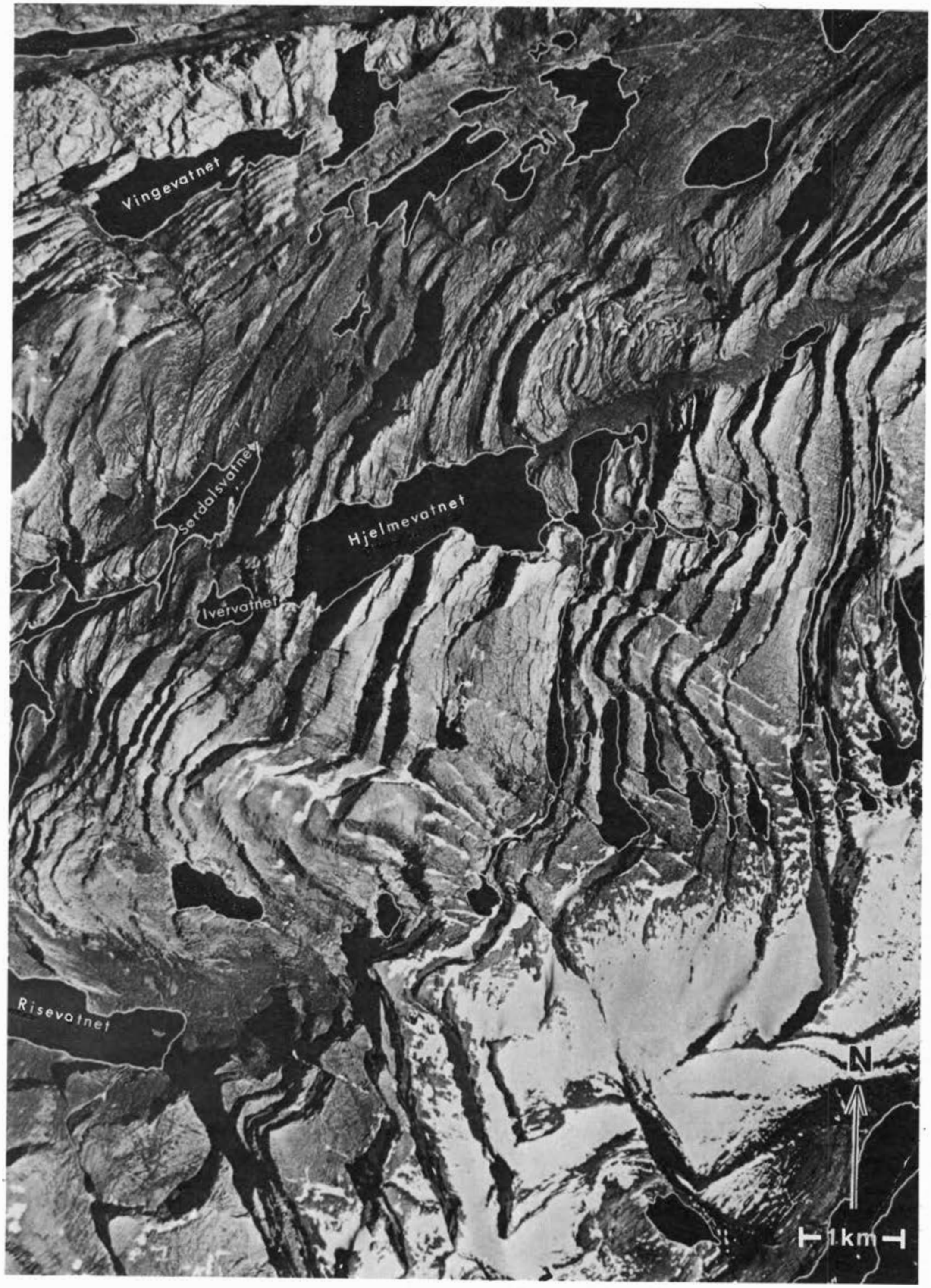
Fig. 10. The Grønedalen syncline. Light units are linear bodies of breccia (conglomerate). Note that coarsening-upward megarhythms in the coarse clastic rocks extend laterally into the sandstone to the left in the picture.

tell exactly whether the material accumulated as bed-load or was emplaced as a single flow (Scott & Gravlee 1968). Debris flows have, however, been observed in action (Johnston 1970) and can be regarded as ordinary and expected events in desert ranges where occasional thunder storm rain flushes most alluvial and collovial deposits completely out of the highlands (Wolley 1946, Beaty 1974). Terrestrial vegetation was scarce during deposition of the Old Red Sandstone and run-off after rain would have been rapid (Schumm 1968). Sheetfloods and debris flows probably followed even moderate rainstorms in the mountains adjacent to the basins.

Steel (1976) noted the much smaller apparent fan radii along the northern margin as compared to along the southern (< 1 km and frequently > 5 km respectively), and inferred that subsidence took place most rapidly or most continuously at the northern edge. Palaeocurrent pattern given in the 'Generalized basin' (Fig. 1 in Bryhni 1975a and Fig. 6 here) indicates that this might be true for the eastern part of the Hornelen basin. But apparent fan radii at the mountain Hornelen to Vingen on the western part of the northern margin are comparable with those of the southern margin (see Fig. 1). What complicates the picture, however, is that some fans along the southern margin are disposed as gently inclined beds in a syncline while those at the northern margin dip steeply below sandstone (associated sandstones are even inverted!).

Sandstone rhythms

The dominant rock type in the interior of the Hornelen Basin is a green sandstone which forms a characteristic topography of monoclinal ridges up to many tens or hundreds of metres high (Fig. 11). Some of these ridges contain megarhythms (Bryhni 1975a, Steel 1976) with distinct sedimentation units of dominantly very fine or fine sandstones at the base and medium sandstones at the tops (Figs 12, 13). The sandstones at the bases of some ridges are often slightly crushed, possibly as the result of bedding plane faulting. Calcareous concretions occur throughout the rhythms but are largest and most abundant in their upper parts.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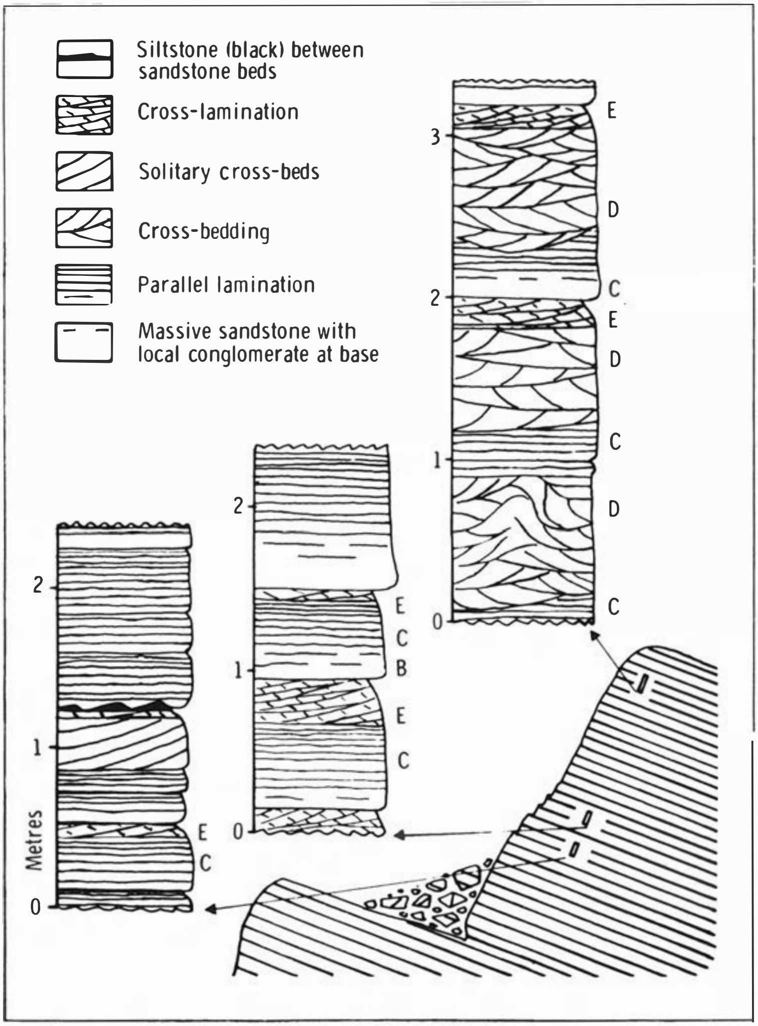


Fig. 12. Partial vertical lithofacies profiles from one ridge, about 30 m high, west side of Risevatnet, Svelgen. (From Bryhni 1975a).

The beds near Svelgen and in other areas of the interior of the Hornelen Basin can be described in terms of five lithofacies which combine to form distinct minor and often fining-upward sedimentation units separated by thin siltstone or erosional surfaces.

Lithofacies A is siltstone (shale) pellet conglomerate, usually a few centimetres thick, or a coarser sandstone with extrabasinal inclusions. It rests either on clearly scoured surfaces of medium sandstone or with only slightly erosional contact on very fine/fine sandstone.

Fig. 11. Aerial photograph mosaic showing marginal breccias at the northern margin (light) and the axial sandstones with megarhythms east of Svelgen. (Copyright Fjellanger–Widerøe.) Each ridge may be up to hundreds of metres high.

Lithofacies B is a massive sandstone, frequently with large calcareous concretions. The interval is up to more than 2 m thick at places and merges gradually upwards into lithofacies C.

Lithofacies C has parallel lamination. Two types can be distinguished: one in the sequences of medium sandstone where it is succeeded by cross-bedded sandstones, and another in the sequences of very fine/fine sandstone where it is topped by thin siltstone or cross-laminated sandstone. The former, occurring in beds often more than a metre thick, have sometimes internal

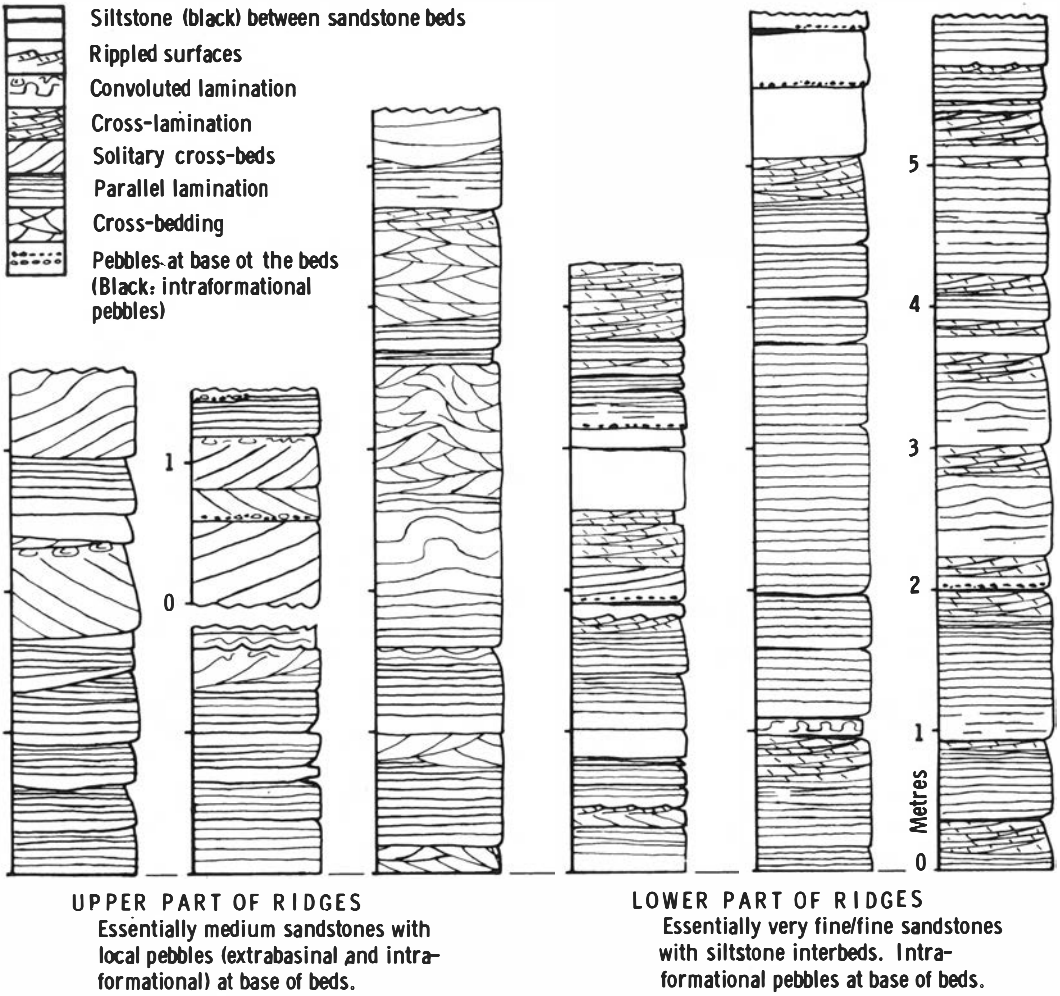


Fig. 13. Partial vertical lithofacies profiles in the Svelgen area.

discordances, local convolutions, diapiric undulations, calcareous concretions, and clasts of shale or siltstone (Fig. 14). They may be easily confused with plane cross-beds in some sections. Some beds have distinct parting in this interval and the flaggy surfaces display flat transverse ripples, unimodal parting lineation, granule lee-side shadows and current crescents (Fig. 15). They must have formed in the higher-flow-regime.

The other facies with parallel lamination is typified by fining-upward intervals, generally 10–50 cm thick. They are made up of very fine or fine sandstone where the parallel laminae become closer spaced upward. Grain-size and association with cross-lamination indicates deposition in the lower-flow-regime.

Lithofacies D is trough cross-bedded sandstone, with sets up to a few metres thick and locally rounded extrabasinal pebbles. The height of each set often decreases regularly upwards, and the trough axes indicate a rather uniform current direction during deposition (see Figs. 5 and 6). Convoluted foresets and diapiric disturbances of cosets are common.

Lithofacies E is composed of cross-laminated sandstone and siltstone which sometimes fine upwards. Ripple crests occur at the top where

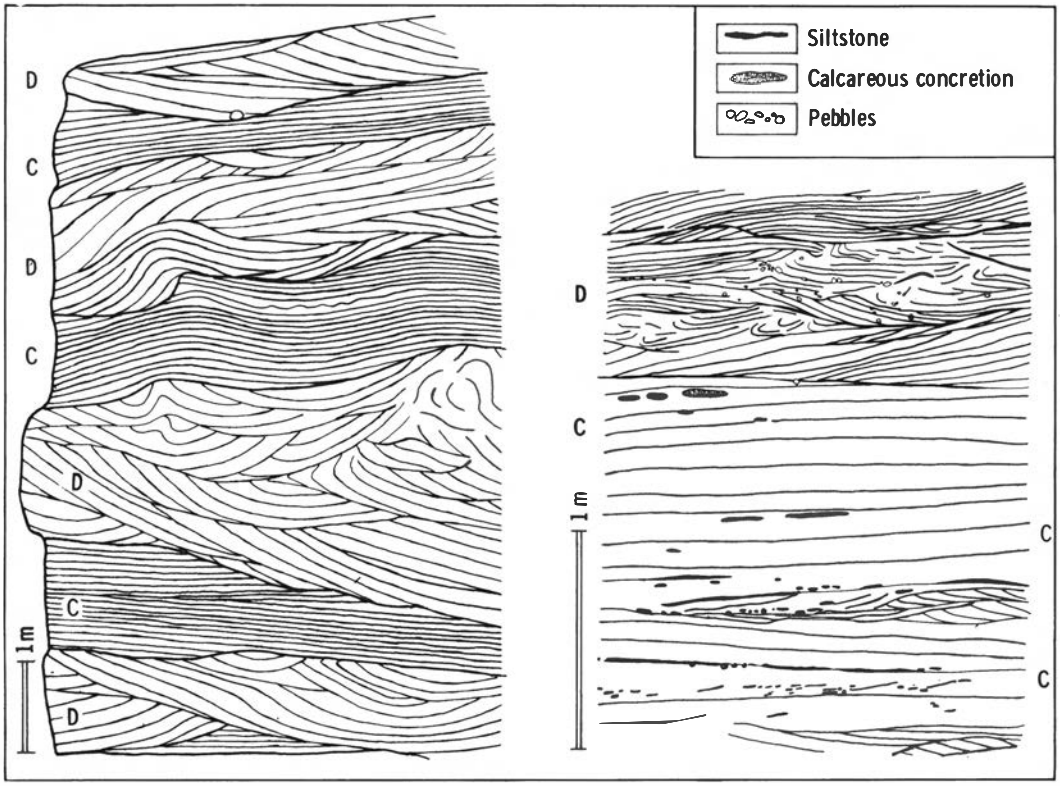


Fig. 14. Sequences of parallel lamination and cross-bedding (CD-sequences) in medium sandstone. Laminae and clasts of siltstone in profile to the right. Left: S shore of Ivervatnet, drawn from photograph. Right: West side of Vingevatnet, drawn on clear plastic overlay.

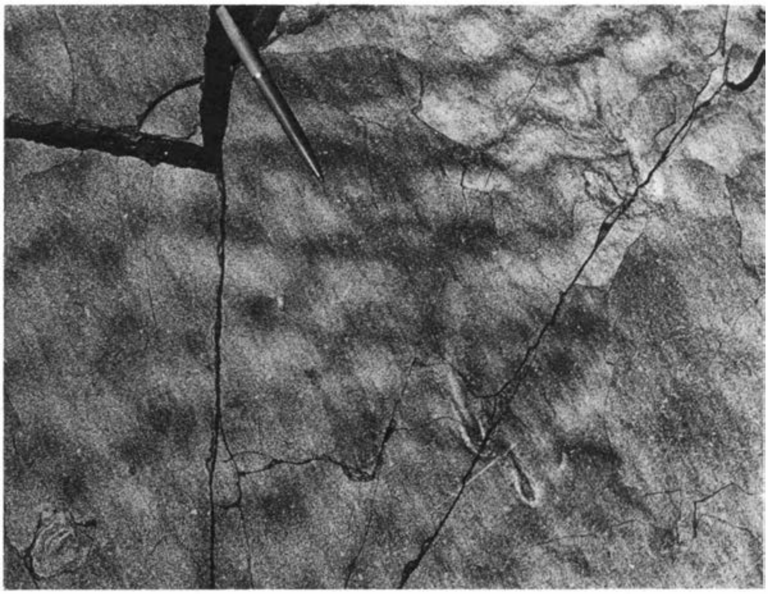


Fig. 15. Parting lineation and current crecents in parallel-laminated sandstone. Road section, Sørdalsvatnet.

beds or laminae of siltstone (shale) less than a couple of centimetres thick may be present. Scouring before deposition of the succeeding bed has in the higher part of the megarhythm often removed the top or replaced it by a conglomerate with clasts derived from the siltstone (shale) interval. The top is often preserved, however, in the finer part of the sandstone sequences and (lower part of the megarhythms) where it may show up as extensive rippled or mud cracked surfaces which occasionally have rill marks, wrinkle marks, rain-drop imprints, plant fossils, and tracks which probably have been produced by small specimens of Merostomata.

Sequence of lithofacies

Long profile measurements indicate that the various lithofacies occur alone or in succession as discrete units. Sequences with only lithofacies C or CD dominate in the coarser interval as units usually less than a couple of metres thick. The finer interval may have C and CD sequences as units usually less than 1/2 m thick, but CE and CDE sequences are more characteristic. The coarser interval has sometimes extrabasinal pebbles on the top of each sequence while the finer interval has only intraformational conglomerates.

Fig. 16 records one of the measured long profiles from the axial part of the basin (cliff west of Hjelmevatnet). The base and upper half represent the coarser interval while the part between 15 and 30 m belongs to the finer interval. A quantitative estimate can be made for the sequences above 30 m and between 15 and 30 m in the profile:

Coarser interval (~42 m thick, 50 sequences with average unit thickness 84 cm)	34%	CD
	30%	C
	14%	CE
	4%	CDE
	18%	Other sequences

Finer interval (~15 m thick, 34 sequences with average unit thickness 44 cm)	29%	CD
	12%	C
	12%	CE
	24%	CDE
	23%	Other sequences

A is often present as an additional lithofacies at the base of the successions.

The sandstone above the measured part coarsens upwards to the top of the cliff where the sequence is dominated by lithofacies C, and unit boundaries are only occasionally indicated by laminae or pebbles of siltstone.

Sequences dominated by lithofacies C have been demonstrated also in the finer interval of long profiles measured at the northern margin (Vingen). The top of these C sequences (beds) have suffered no or only shallow erosion. Structures indicating very shallow water or subaerial exposures (patterned cones, rain-drop imprints) are preserved on the top of the beds in this area. Corresponding dominance of C sequences is characteristic for sandstones in the westernmost part of the district.

The finer interval in a long profile measured at Svelgen in the axial part of the basin has much more CD and CE sequences (respectively 33% and 60%) than tabulated above. Thus the relative abundance of the various lithotypes and successions varies both with position in the megarhythm and location within the basin.

Interpretation

The smallest rhythms in the sandstones in the axial and main part of the Hornelen Basin fine upwards or have one or more of a few lithofacies types in a regular sequence which may be truncated by erosion on the top. They are sedimentation units in the sense of Glennie (1970): one or more sets of strata deposited continuously under uniform or continuously varying conditions which constitute *minor rhythms* within the much larger coarsening-upward units.

Lithofacies A to E were related to bedforms produced from bedload while the intervening very thin siltstone beds or drapes were deposited out of suspension. The top of the beds were occasionally exposed at the surface and in places wet sand rose up diapirically through the desiccation cracks. The various lithofacies types are mostly confined to individual beds a few decimetres to a few metres thick and are thus of smaller scale than the fining-upward cycles formed by lateral migrating point bars (Allen 1965) of meandering streams. Only in the eastern part of the district (Hyen–Svartevatn) have cycles of the right scale and with enough siltstone for such interpretations been recorded as yet. Everywhere else the large fractions of parallel-laminated sandstone with unimodal lineation, occurrence of extrabasinal pebbles, frequent

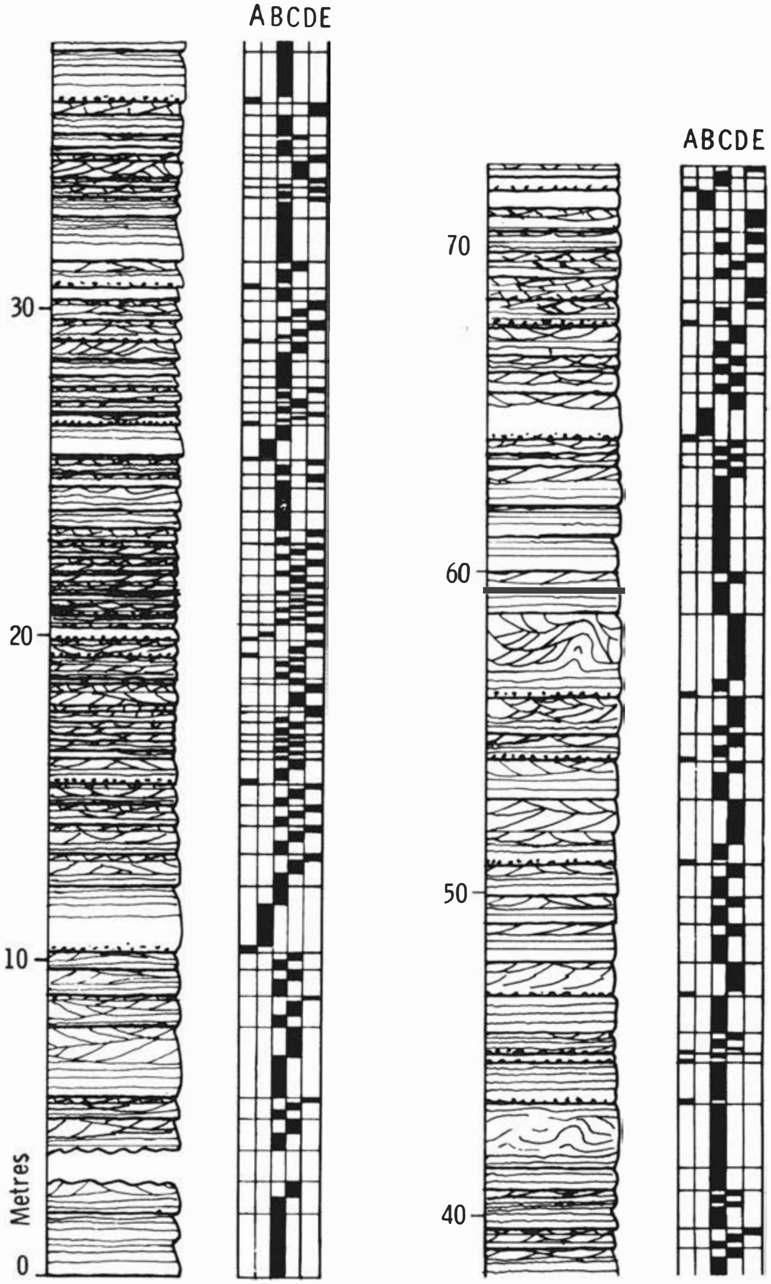


Fig. 16. Vertical lithofacies profile measured in the cliff west of Hjelmevatnet, between about 385 and 450 m a.s.l. Lithofacies A–D are described on pp. 285–288.

cross-bedding with narrowly ranging directions of trough axes, and mud- or siltstone only as intraformational pebbles or thin drapes between the beds indicate that deposition took place from low-sinuosity, braided or unidirected streams under declining flow regimes of individual floods. Sequences similar to the minor rhythms recorded from the Hornelen Basin have been discussed by Moody-Stuart (1966), Collinson (1970), Friend & Moody-Stuart (1972), Leeder (1973), Picard & High (1973) and Allen (1974).

Fining-upward rhythms from recent braided stream deposits have been attributed to deposition with waning current velocities as a channel is gradually filled (Coleman 1969, Williams & Rust 1969). A lower coarse unit of large-scale cross-bedding and higher finer units with cross-lamination, parallel lamination, and convoluted bedding are characteristic. Channel fills between relatively stable braided river bars have basal cross-bedded sands which pass upwards and outwards into sands with plane lamination, which in turn are followed by ripple cross-laminated sands towards the channel edges (Eynon & Walker 1974). Lateral migration of such shallow channels would account for fining-upward sequences, but the very extensive and regular development of each sedimentation unit and few deep scours in the Hornelen sandstone call for a mechanism which involved major parts of the basin at each depositional rhythm, e.g. floods. Support in favour of this comes from the fact that sequences similar to those illustrated in Figs. 12–16 have been recorded from modern floods by McKee et al. (1967), Coleman (1969), Williams (1971, see plate VII A and fig. 9) and Eynon & Walker (1974).

The profiles reported by Steel (1976, fig. 3) differ from those discussed here and by Bryhni (1975), since they show only minor parallel laminated beds but up to 5 m thick cross-bedded sequences in the coarser part of the megarhythms. Steel records no minor fining-upward subunits within the sequences. This difference can be related to the presence of more permanent channels in the area studied by Steel, or – alternatively – to the figure being necessarily simplified.

Frequent internally contorted laminae, patterned cones, and mud cracks where sand rose diapirically testify that the water pressure was locally high during deposition of the sandstones. This might again indicate that the depositional surface was slightly inclined, and, from paleocurrent evidence, we can infer alluvial slopes that spread westwards by valley floor sedimentation between rising escarpments. Rapid run-off after rain, prior to widespread terrestrial vegetation, would have resulted in a sheetflood followed by formation of braided streams because of an overload of sediment, sub-aerial exposure of sediments, and confinement of the reduced volume of flowing water to river channels (Schumm 1968, Glennie 1970). In the Hornelen Basin, the finer intervals of the megarhythms were probably related to overbank flooding and the coarser intervals to flooding in the main channels.

Carbonate cement and calcareous concretions probably formed by precipitation from groundwater when the water level fell slowly between the floods. The fact that the largest and most frequent calcareous concretions occur in the coarser intervals can be related to Glennie's (1970) observation that the strongest cementing action in alluvial deposits of modern deserts appears to be confined to the main wadi channels.

Green and red, very fine sandstone and siltstone near base of the succession

Formation III near the base of the Hornelen Group occurs between clastic rocks assumed to have been derived from quite different sources (see deduced paleocurrents in inset, Fig. 5). Does this formation represent:

lake deposits between eastward aggrading alluvial fans and westward aggrading alluvium of the valley floor,

flood basin deposits or

the distal part of an alluvium wedge which originated in the east?

Formation III on Batalden (p. 274) is probably equivalent to a fine-grained unit which occurs between breccia (below) and conglomerate (above) at Kvannhovden 10 km to the north-northeast.

The latter unit is about 50 m thick and is composed of medium grey-green sandstone with minor cross-lamination below red-brown sandstone/siltstone. The upper 8–9 metres of the red-brown sandstone/siltstone succession below an erosive roundstone conglomerate (Fig. 17) display the following characteristic features:

1. Alternation of beds 5–10 centimetres thick, which frequently are graded with red-brown medium sandstone at base and red fine sandstone/siltstone at the top. Closely spaced joints oblique to the bedding are preferentially developed in the upper (fine) part of the beds and tend to accentuate the grading.
2. Constant thickness of the beds within the outcrop (~5 m) and flat or rarely load-casted (flumed) base.
3. Parallel lamination in the lower part of most beds and distinct current lineation are well-exposed in one flaggy bed. Cross-lamination occurs locally at the base, but is more common in the

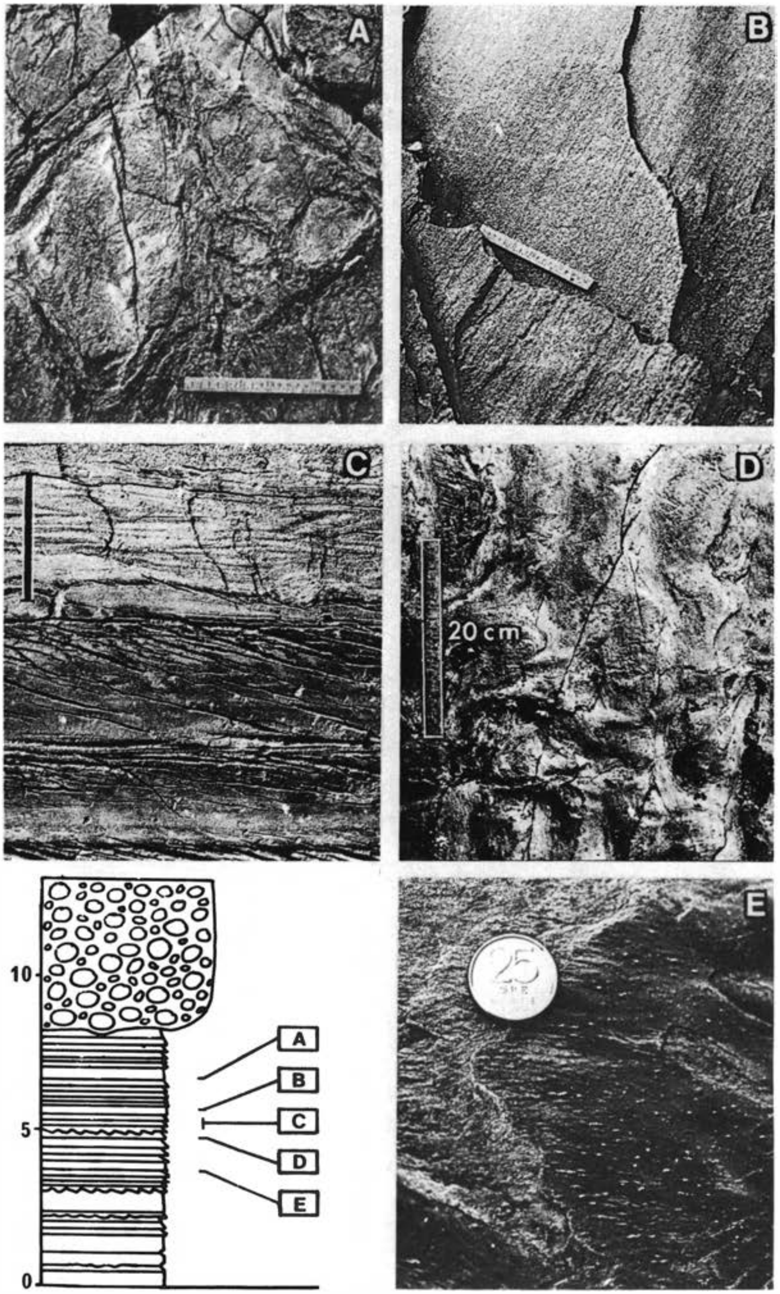


Fig. 17. Structures in red sandstone/siltstone sequences at Kvannhovden. Bar or scale is 20 cm long, coin is 1.7 cm in diameter.
A. Part of extensive mud-cracked silty surface with sandstone dykes.
B. Current lineation in flaggy sandstone.
C. Graded beds, with oblique joints preferentially developed in the upper (finer) part of each unit.
D. Part of extensive rippled surface with local striae (tool marks). Ripples and striae most likely indicate sedimentary transport towards NNW (left in picture).
E. Minor mounds on smooth, silty surfaces, possibly wrinkle marks.

finer-grained, higher part of each bed. Siltstone inclusions occur at places.

4. The boundary between many beds are developed as extensive siltstone surfaces with either ripples, mud cracks, striae, and minor mounds which might be wrinkle marks. The shrinkage cracks are filled by coarser sandstone from below. Some of the striae might possibly have formed as intersections between closely spaced joints and the bedding, but they are most commonly tool marks (grooves).

5. Direction of sedimentary transport appears to

be towards WNW, but the vector evidence (ripples, cross-lamination, current lineation, striae) is not quite conclusive within the small outcrop.

Interpretation

The regional development of the fine-grained succession and its location to an assumed low area in the basin favour interpretations in terms of a lacustrine environment. This cannot be reconciled, however, with evidence from the rock colour and the sedimentary structures. Red colour implies that destruction (oxidizing) of organic matter has taken place and either shallow depths or only temporary water coverage must be assumed. Sedimentary structures at Kvannhovden indicate that many beds were deposited under lower-flow-regime waning currents, but local good parting lineation indicates that deposition also reached the upper-flow-regime conditions at times. The fine-grained, mudcracked top of some beds indicates intermittent emergence of the sediment surface during deposition. Thus the sedimentary environment was probably one of a periodically flooded basin or distal alluvial plain rather than one of a permanent lake.

Very fine sandstone/siltstone interbedded with fanglomerate

Very fine sandstones and siltstones occur along the whole northern and southern margins of the sandstone body of the Hornelen Basin, i.e. along the line of interference between the marginal fanglomerates and sandstones of the middle part of the basin. They pose the same problem as Formation III in the western part of the district: are they lacustrine, flood basin, or distal fan deposits?

An example from near Gjegnalund on the northern margin is illustrated in Fig. 18. The 'Very fine sandstone/siltstone' seen on the map is situated between original fanglomerates derived across the northern margin and rhythmic sandstones transported from the south (see rose diagrams in Fig. 6). Primary linear structures within the unit of very fine sandstone trend parallel to the northern margin, e.g. perpendicular to the transport of the associated sediments.

The unit has continuous, parallel, and extensive beds (Fig. 19) with grey-green, purple, and red-brown colour. Parallel lamination, cross-lamination, convoluted lamination and small concretions are common within the beds, but do not occur throughout the section. The cliff illustrated in Fig. 19 is made up mainly of siltstone with parallel lamination overgrown by calcareous concretions. This particular rock has subconchoidal fracture, poor fissility, and calcite content which is exceptionally high and sometimes concentrated in white laminae 1–3 mm thick. Unlike most other rocks within the Hornelen Basin, this regularly bedded siltstone appears to have been deposited in quiet water.

Other varieties within the unit of very fine sandstone/siltstone have, however, various primary sedimentary structures which indicate both currents and local emergence of the sediment surface during deposition.

Another, more easily accessible locality for observing a thick succession of very fine sandstones and siltstones occurs in the lower part of Myklebustdalen. Beds of very fine sandstone are here separated by red-brown or green siltstone a few millimetres or rarely up to a few centimetres thick. Intercalations of breccia, conglomerate, and coarse granule-stone have usually channelled based and more rarely internal cross-bedding and imbricated clasts.

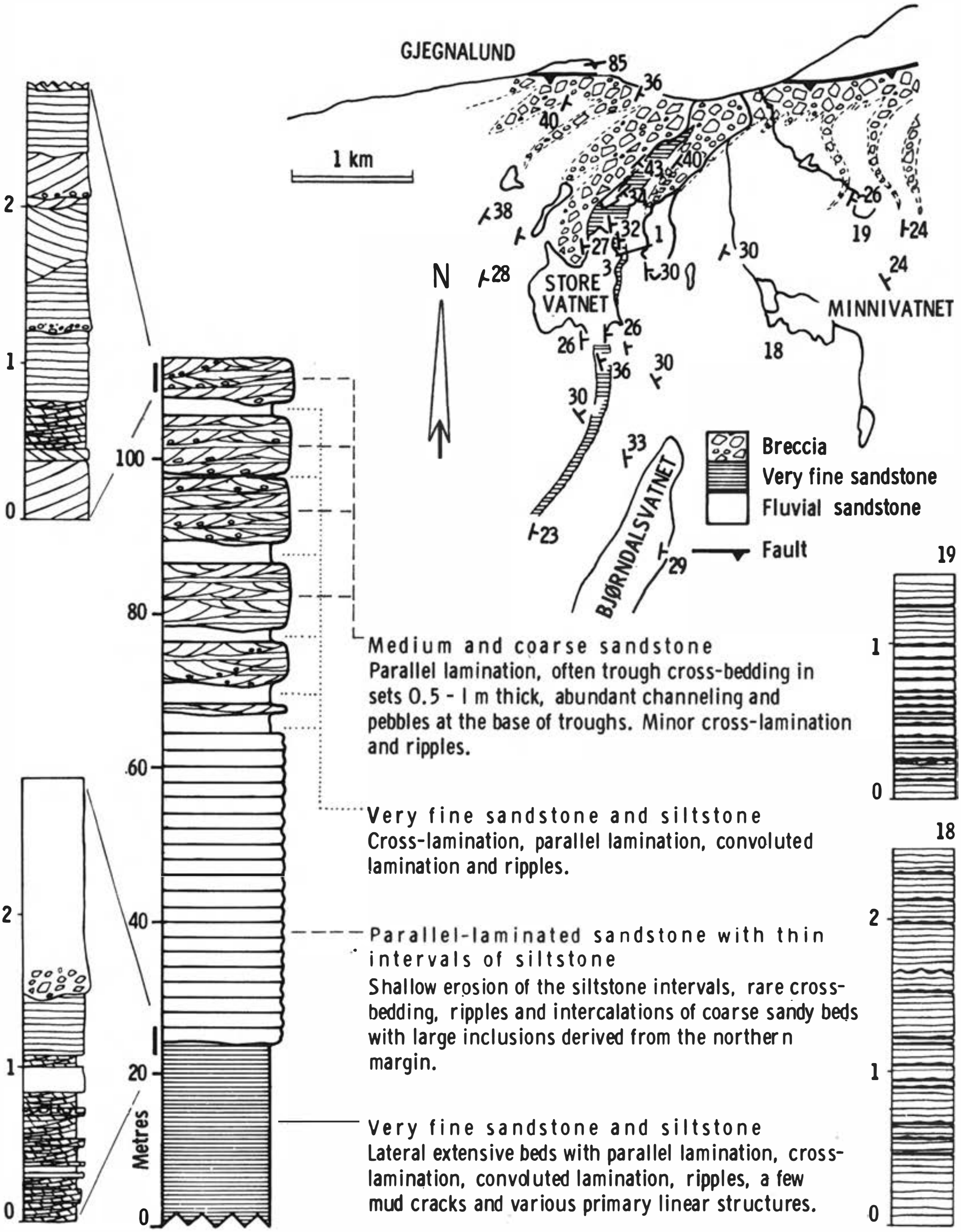
A succession of 27 measured beds has an average thickness of 12 cm and extend laterally with unmodified thickness within the exposure. Most beds are massive, with parallel lamination, or have cross-lamination and convolute bedding. Extrabasinal clasts up to 30 cm in diameter occur in some of the beds of fine-grained sandstone, and there is usually a distinct break to the overlying siltstone. A few beds have intraformational clasts of siltstone (Fig. 20A).

The thin siltstone intervals between the very fine sandstone beds in Myklebustdalen are characterized by these features:

They form extensive red-brown surfaces with a brick red colour when slightly tectonised by differential movements between the more competent beds.

There was no or only insignificant erosion before deposition of the succeeding bed of very fine sandstone. The upper part of some siltstone interbeds has been split and bent upwards, with very fine sandstone filling the original hollows (Fig. 20B).

There are abundant bedding surface structures like:



Medium and coarse sandstone
Parallel lamination, often trough cross-bedding in sets 0.5 - 1 m thick, abundant channeling and pebbles at the base of troughs. Minor cross-lamination and ripples.

Very fine sandstone and siltstone
Cross-lamination, parallel lamination, convoluted lamination and ripples.

Parallel-laminated sandstone with thin intervals of siltstone
Shallow erosion of the siltstone intervals, rare cross-bedding, ripples and intercalations of coarse sandy beds with large inclusions derived from the northern margin.

Very fine sandstone and siltstone
Lateral extensive beds with parallel lamination, cross-lamination, convoluted lamination, ripples, a few mud cracks and various primary linear structures.

Fig. 18. Geological map and measured profiles south of Gjegnalund at the northern margin of the Hornelen Basin. (Profile symbols as in Figs. 12 and 13.)

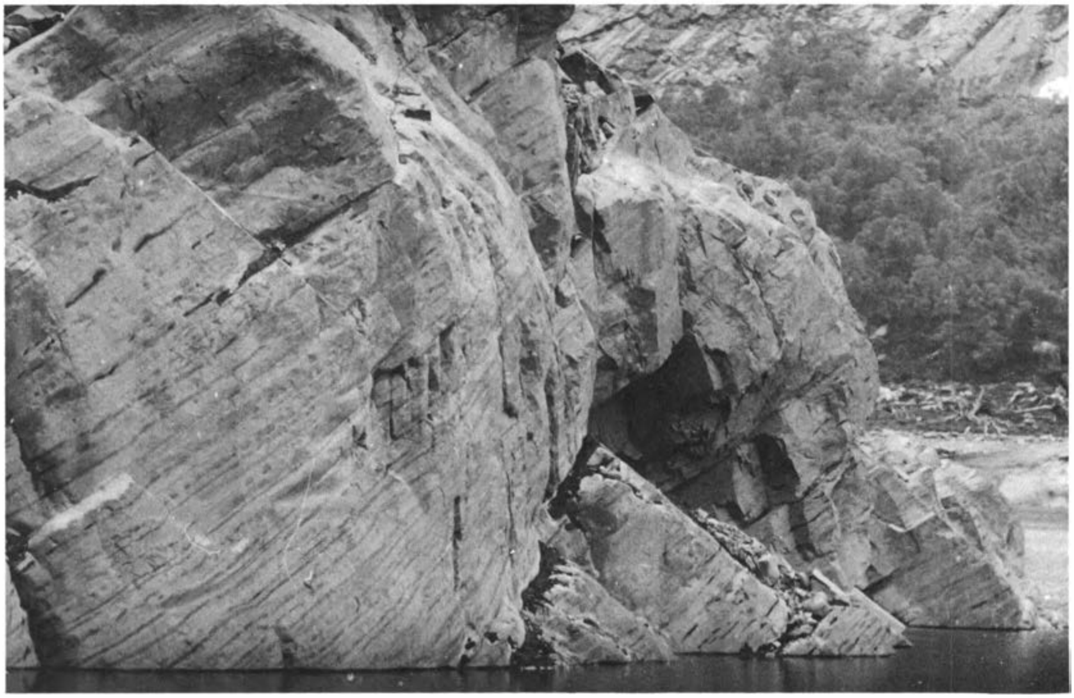


Fig. 19. Regularly bedded concretionary, very fine sandstone and siltstone at east shore of Storevatnet south of Gjegnalund.

mud cracks filled by sandstone from the bed below (Fig. 20 C),

very abundant irregular linear structures which are supposed to be wrinkle marks (Fig. 21 C),

flute-like linear structures and grooves (Fig. 20 D, E),

ripples of parallel, lingoid and caternary types,

rain-drop imprints, often preferentially developed on the crests of ripples (Fig. 20 F),

conical depressions with smooth or patterned sides, up to more than 50 cm wide and 12 cm deep on mud cracked and rippled surfaces.

Interpretation

The rather well-bedded very fine-grained sandstones and siltstones along the northern margin are in many respects similar to those of the finer interval of the major sandstone megarhythms and those of Formation III on the westernmost islands. The map and sections illustrated in Fig. 18 indicate, however, that they form a distinct formation which intertongues northwards into fanglomerates and southwards into sandstones with coarsening-upward megarhythms (where profiles 18 and 19 in Fig. 18 display mainly C sequences of the finer interval). It is also significant that their primary lineations trend WNW–ESE, quite different from the inferred transport of associated fanglomerates and megarhythmic sandstone (see Fig. 6).

Parts of the very fine sandstone/siltstone near Gjegnalund (Figs. 18 and 19) may have formed in temporary lakes between alluvial fans from the north and alluvial slopes from the south or south-east. Especially suggestive for such an origin is the regular bedding with few current structures, high carbonate content, and the lack of evidence of intermittent emergence of the sediment surface during deposition. The 'lakes' have probably not lasted long, for closely associated fine-grained sediments display a variety of primary linear structures formed by flowing water as well as a few mud cracks indicative of intermittent emergence. Any 'lakes' in this area during deposition were thus probably only food-controlled shallow ponds which were elements in the fluvial system. A floodplain environment is more likely than distal-fan, because the primary

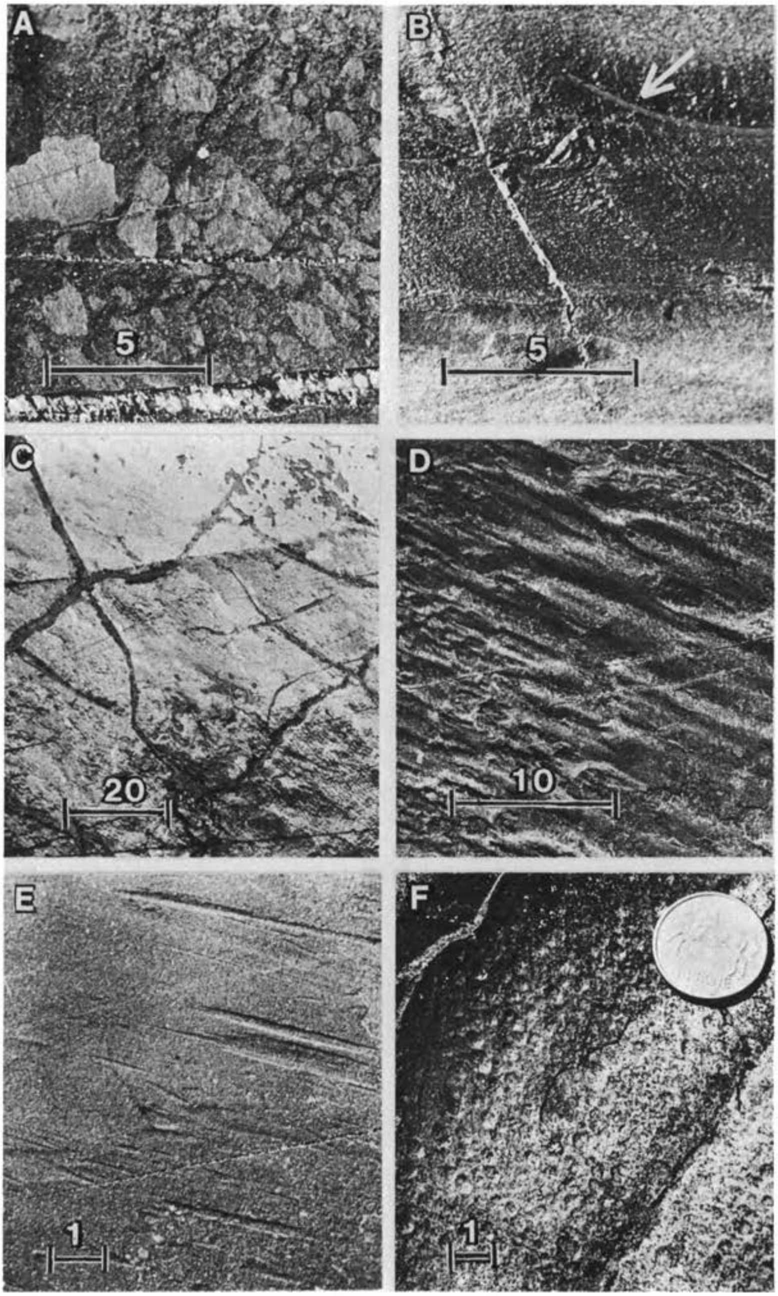


Fig. 20. Structures in very fine sandstone near the northern margin (scale in cm). All photographs are from road sections in Myklebustdalen, above Vik, Ålfoten.
A. Mud pellet conglomerate.
B. Split and broken siltstone laminae (white arrow) between two beds of sandstone.
C. Mud cracks with possible wrinkle marks on mudstone drape.
D. Linear structures on top of sandstone beds.
E. Tool marks (grooves) on top of sandstone beds.
F. Rain-drop imprints.

linear structures trend perpendicular to the assumed transport direction of associated sandstones.

The very fine sandstones/siltstones of Myklebustdalen have probably also been deposited in a floodplain environment. Most of the evidence is found in the structures in the siltstone between the sandstone beds:

Some of the cracks have been filled by sand from below and must indicate a desiccated surficial cover through which wet sand was able to rise diapirically. Moreover, the mud was sufficiently rigid to be preserved as delicate flakes or curls below succeeding beds and even redeposited as clasts in intraformational conglomerates.

Linear structures assumed to be wrinkle marks are associated with mud-cracked siltstone drapes and have probably formed in sediments covered only by a thin film of water (Reineck 1969). Conical depressions in the rippled and mud-cracked surfaces have probably formed by water welling up through unconsolidated very fine sandy sediments. There are no external rims, which probably indicate that there was only a very thin water cover during formation (Boyd & Ore 1963, Bryhni 1976).

Rain-drop imprints occur at places and must represent periods of sub-aerial exposure.

Primary sediment lineation indicates sediment transport towards W, e.g. parallel to the northern margin.

These points suggest that the very fine sandstones along the northern margin were deposited in shallow water flowing westwards along the basin margin and that the tops of the beds were exposed between each depositional episode. No evidence has been seen of minerals formed by evaporation of water, other than calcite which occurs as a replacement product of detrital minerals in calcareous concretions, and might have formed by ascending ground water. The depositional environment for the very fine sandstone sequences must thus be that of a flood basin in the alluvial valley rather than that of a playa-like intermittent lake. Frequent cross-lamination in the very fine sandstones, lingoid ripples, and tool marks on the bedding surfaces are evidence of currents operating in the lower-flow-regime. Again, the deposits may be confidently related to floods extending over the low, temporary banks of channels in the alluvial slope and flowing westward, along the feet of fans fringing the northern margin of the basin. The currents were rarely strong enough to cut into already indurated surfaces of previous flood deposits, but picked up cobbles from the distal parts of the marginal alluvial fans. At times, the sheets of coarse rubble from the northern margin aggregated over the valley floor deposits or became interbedded with them.

Development of megarhythms

The thick sequences of coarse clastics along the margins of the Hornelen Basin can only be explained by the presence of steep associated slopes during deposition and rejuvenation of these slopes by contemporaneous uplift. There are dislocation zones in the basement which parallel the northern and southern marginal faults of the basin; some of these might have been active by vertical and/or strike-slip movements during deposition of the Devonian sediments.

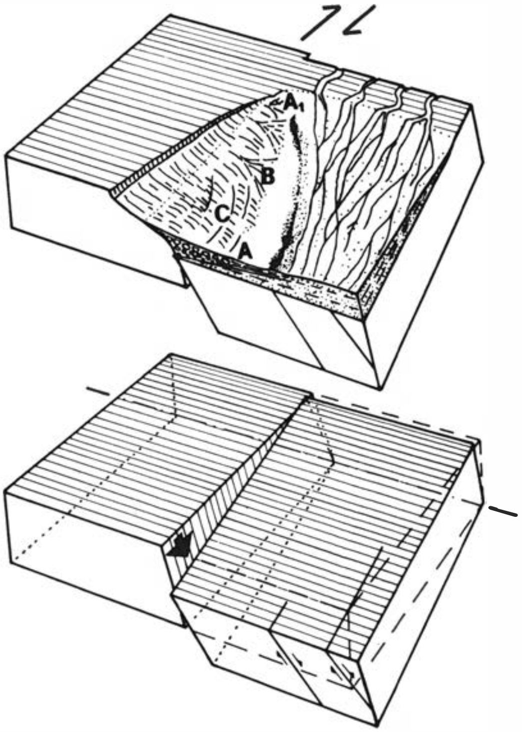


Fig. 21. Development of sequences of alluvial fans at the foot of a laterally migrating hinge fault.
A, A_1: Flood plain/alluvial slope deposits unrelated to the fault.
B and C: Coarsening-upward alluvial fan deposits related to the fault scarp.
A, B and C can also be understood as the time sequences formed successively at the foot of a normal fault by basinward fan progradation.

It is more difficult to explain the coarsening-upwards of many breccia, conglomerate, and sandstone sequences. A suggestion of progressive spreading of braided river bar sediments across the floodplain, tectonic pulses and climatic changes were made by Bryhni & Skjerlie (1975) to account for sandstone sequences of another district. Similar mechanisms were discussed by Bryhni (1975 a) and Steel (1976) for the Hornelen Basin. In the following, emphasis will

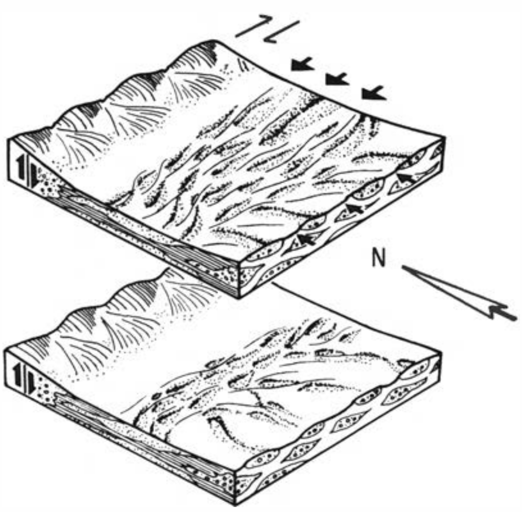


Fig. 22. Model for deposition in the Hornelen Basin (middle part). Palaeoslope indicated by black arrows pointing from east to west. Sediments were derived from braided rivers in an alluvial valley along the feet of fans fringing the northern fault scarp. Normal and transcurrent fault movements occurred along this northern margin. The upper diagram differs from the lower by showing channels over the entire basin, e.g. the condition during floods.

be laid on two mechanisms: Cycles of fan/alluvial slope development in an area adjacent to periodic tectonic uplift and tilting, possibly with lateral shift of channels and banks; alternatively climatic variations.

A cycle of normal fan evolution will involve basinwards progradation, the development of a graded profile, and formation of a rock pediment, with sheetfloods most pronounced when a graded stage has been reached (Davis 1938, Blissenbach 1954). The initial stages of fan transgression onto the valley floor must give coarsening-upward vertical sequences similar to those of deltas and other regressive shorelines. With maturity, these fan sequences may fine upwards due to general denudation and fault scarp retreat (Bluck 1967).

Repetitive cycles of stream or streamflood deposits with overlying sheetflood deposits may be caused by rivers flowing along the fan bases. Blissenbach (1954) mentions an example where channels in the fan were filled by stream or streamflood deposits when a river migrated away from the fan base; upon establishment of a graded course, sheetfloods contributed to the building up of the fan. This mechanism is attractive in the Hornelen Basin where fans along the southern and northern margins extended into an alluviated valley, but can only be understood as the consequence of epeirogenic tectonic movements, which are likely to have occurred along the northern and southern margins of the original basin.

Erosion and deposition along tectonically uplifted mountain fronts sometimes do not keep pace with the relative positions of highlands and basin floor. Thus Steel & Wilson (1975) advocated increased rates of uplift in the source areas to explain coarsening-upward conglomerate sequences in the (?) Permo-Triassic of Scotland, and Wolburg (1961) explained coarsening-upward clay to sandstone sequences in the Buntsandstein of NW Germany by epeirogenic movements. A recent example can be seen in Death Valley of California, where eastward tilting of the valley floor causes burial of an unknown volume of the eastern marginal fans beneath valley (saltpan) sediments. If no further deformation takes place, Denny (1965) estimates that the eastern fans will probably grow in surface area until they are two or three times their present size. Periodic tilting or uplifts along the eastern border would thus probably produce a sequence of transgressive fans, e.g. upward-coarsening rhythms in vertical sections such have been recorded in the Hornelen Basin.

Regression of the fans will produce vertical sequences from coarse proximal fan facies at the base to distal facies at the top, as found in the Van Horn Sandstone of Texas (McGowen & Groat 1971). In the Hornelen Basin most megarhythms – both in the marginal fanglomerates and in the axial sandstones – coarsen upwards. This could indicate that the vertical successions reveal essentially prograding alluvial fans and alluvial slopes, e.g. from more distal to more proximal fan up-section.

Uplift along the margin of the basin can have been accompanied by strike-slip movement (Steel 1976), or the fault may have been a migrating hinge fault as speculated upon by Bryhni (1964a). The leading edge of a hinge fault (Fig. 21) will be fringed first by sands deposited by streams flowing along the alluvial slope of the basin (A_1) and subsequently by coarser clastic material washed over the fault scarp (B). The juvenile fault scarp would be attacked by weathering and retreat parallel to itself with an apron of progressively wider pedimont. The graded detrital slope would now favour formation of sheetfloods (C). Subsidence and tilting of the previously deposited sediments would finally permit incursion of rivers from the valley floor over the marginal fan bases and begin the new cycle. The hypothesis of migrating basin is yet unproved, but the illustration in Fig. 21 can be used also to explain the cycle of fan evolution on a normal fault scarp.

Lateral shift of the depositional area is common on alluvial fans. When one section of the fan has been built up, the streams shift to another, lower section of the fan and build that up (Denny 1965). Costello & Walker (1972) suggest that coarsening-upward clay–silt–sand–gravel sequences in a braided river are deposited from water which spills in increasing amounts over the levées of an active channel. The upper, coarse sediments represent final breaching of the levée, rapid increase in discharge, and introduction of much more bed-load to the newly active channel.

Such a mechanism is attractive both for the marginal breccias and the axial sandstones in the Hornelen district. Some of the sandstone sequences are similar to those of crevasse splays (Coleman 1969) and it can be suggested that megarhythms of very fine to medium sandstone are related to transitions from floodplains via bank overtopping to gradual establishments of new shallow braided river channels.

Extensive ephemeral flooding, rapid subsidence, and ample supply of sediments would make transitions between the overbank and shallow channel deposits gradational without major bank erosion. The channel sands aggraded over the alluvial slope and produced extensive sheets of coarser above finer sands. Pulsatory tectonic activity along the marginal faults and eastward displacement of the entire basin as postulated by Bryhni (1964 a, b) and Steel (1976) would emphasize the coarsening-upward megarhythms.

The development of some megarhythms over the entire basin (see Figs. 10 and 11) is hard to explain wholly by the essentially tectonic/autocyclic mechanisms above. Marginal fanglomerates and axial sandstones apparently became coarser simultaneously over large areas, and similar megarhythms are found in adjacent basins (Bryhni & Skjerlie 1975, Steel 1976). This suggests that climatic factors may also have been involved.

The climate was hot over much of the Old Red Sandstone landmass, with seasonal rainfall in the south and more abundant and evenly distributed rains in the north (Woodrow, Fletcher & Ahrnsbrak 1973). The Norwegian Old Red Sandstone pole was located about 160°E, 20°N (Storetvedt 1967) and the Hornelen Basin was thus not far from the Middle Devonian palaeoequator at the time of deposition. Drought periods might have resulted in reddening of surficial very fine sands and silts and to formation of calcareous concretions, but the general lack of caliche and the dominance of green sandstone in the Hornelen Basin indicates that the climate for most of the time was rather wet.

The amount of present-day sedimentation increases with precipitation when the climate is relatively dry, but decreases again and remains nearly constant at higher rates of precipitation. Swann (1964) used this relationship to explain how climatic variations in the river source area could be related to rhythmic sedimentation: clastic units resulted when the river prograded its delta across the gradually sinking basin while limestone developed when the river could not supply enough sediment to offset continued sinking.

Before the appearance of land vegetation, both sediment yield and run-off increased generally with precipitation, and run-off occurred more frequently as flood (Schumm 1968). Given that a large number of the beds in the Hornelen Basin do in fact represent sheets deposited by single floods, then the megarhythmic variations could be attributed to changes in discharge, e.g. periods with smaller and larger floods (Fig. 22). The finer part of the successions may represent relatively dry periods with floods essentially in the lower-flow-regime and the coarser parts represent relatively wet period with floods essentially in the higher-flow-regimes. Coarsening upward megarhythms can then be related to increased flood discharge until most of the available sediments were swept out as a prograding sheet.

The recurrence of similar megarhythms throughout the entire stratigraphic succession would require a regularity of climatic fluctuations which is rather unlikely (Steel 1976). Climatic control is therefore provisionally accepted to be of less importance for production of the successions than tectonic pulses with consequent sedimentation, but we cannot quite disregard seasonal climatic fluctuations as the cause of some of the observed rhythms. Another, fascinating but yet unexplored, possibility is that there are geotectonic pulses with subsequent effects on climate at the final stage of the Caledonian orogeny.

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