Coarsening-upward cycles in the alluvium of Hornelen Basin (Devonian) Norway: Sedimentary response to tectonic events

R. J. STEEL
S. MÆHLE*
H. NILSEN*
S. L. RØE*
Å. SPINNANGR*

Geological Institute, University of Bergen, 5000 Bergen, Norway

ABSTRACT

Hornelen Basin (Devonian) is filled with ~25 km of sediments, mostly sandstones. These sedimentary rocks are spectacularly organized into more than 150 basin-wide cycles, each on the order of 100 m thick, most of which coarsen upward. The cycles are otherwise complex, consisting of marginally derived fanglomerates and laterally equivalent, longitudinally dispersed alluvial plain sediments.

The basin-wide nature of the cycles, the fact that the coarsening upward occurred at the same time in both marginal and axial facies, and because successive alluvial fan bodies coarsen upward whether they are composed of debris flow or of stream deposits suggest that the cycles are allocyclic and that they are the basin's response to the lowering of its floor. In their marginal development, the cycles are commonly segmented, consisting of coarsening-upward subcycles of the order of 10 to 25 m thick. The geometry and internal details of these suggest that they also were tectonically generated.

It is likely that the 10 to 25-m coarsening-upward sequences, representing aggrading base-level conditions, were the basic sedimentary response to basin-floor subsidence. The 100-m cycles represent additional complexity in style of subsidence. Progressive eastward overlap of successive 100-m units suggests that at this interval the locus of subsidence abruptly shifted in a proximal direction, by ~0.25 km.

A dextral wrench fault model is proposed to account for this pattern of basin filling.

INTRODUCTION

Descriptions of sedimentary successions with inferences about tectonic control on sedimentation are legion, and this is hardly surprising in view of the fact that the major control on almost all sedimentation is tectonic. The critical question is how the control operates (Blatt and others, 1972, p. 591). A weakness in many of the published cases is that arguments are generalized and usually uninformative as to how a relationship develops and is maintained between the two sets of processes.

We suggest that some insight to the relationship may be gained by closer examination of trends of sedimentation in time in alluvium-filled basins, particularly in basins whose geologic context and general sedimentary attributes are such as to suggest, *a priori*, that tectonism was a dominant external control during sedimentation.

Cases in point, presently being restudied, are the three main Devonian basins of western Norway (Solund, Kvamshesten, and Hornelen Basins). All three were supposedly tectonically controlled (Nilsen, 1968; Skjerlie, 1971; Bryhni, 1964b), although in none of these studies has that conclusion been made by inductive reasoning, because no detailed facies analyses or detailed sedimentary successions have been published. In these cases, a general feature of interest is the difference in coarseness of the alluvial sediment pile in the different basins. Solund Basin is filled with 4 km of conglomerates, whereas Hornelen Basin apparently contains 25 km of sediment that is made up largely of sandstones. If the notion that tectonism was the dominant control of sedimentation is true (and varying climatic or lithologic controls can probably be ruled out because the basins are sited close together and each lies within an equally varied assemblage of source rocks), then there is clearly scope for a more detailed discussion of how differences of tectonic style or intensity have produced such a varied sedimentary response (Steel, 1976).

In the present discussion, we are concerned primarily with a particular feature of the internal organization of one of these basins, Hornelen Basin. This is a basin-wide cyclicity, usually expressed as repeated coarsening-upward sequences of the order of 100 m thick and that is developed equally well in the sandstone portion of the fill (basin-axis) as in the conglomerate portion (marginal). In making a case for the tectonic generation of this cyclicity, we emphasize its development in alluvial plain facies. The internal details and geometry of individual fan-floodplain bodies give relatively short-term evidence of the sedimentary response to individual periods of faulting or subsidence. The geometrical relationships of successive bodies (the way in which they are stacked) give longer term evidence concerning the locus and changing style of tectonism in time.

HORNELEN BASIN

Hornelen Basin is relatively small (< 2,000 km^2) and is filled with Devonian alluvial sediments of two main types. Minor amounts of conglomerate occupy the marginal areas adjacent to the present northern and southern bounding faults (Fig. 1). These deposits were dispersed laterally across the margins on alluvial fans which, on the basis of paleocurrents, sediment coarseness, and pebble size changes, headed either from the present fault lines or from parallel faults not far outside the present basin boundaries (see Fig. 8). Most of the basin, however, is filled by sandstones which probably accumulated from westward-flowing rivers on a broad alluvial plain (see Fig. 8) (Bryhni, 1964b). A marginal interfingering of these deposits with the fanglomerates suggests that at certain times the entire width of the basin was flooded by the longitudinal alluvial plain system.

---

* Present addresses: (Mæhle and Spinnangr) Statoil, Lagårdsvn. 78, 4000 Stavanger, Norway. (Nilsen and Røe) Oljedirektoratet, Lagårdsvn. 80, 4000 Stavanger, Norway.

Geological Society of America Bulletin, v. 88, p. 1124–1134, 8 figs., August 1977, Doc. no. 70808.

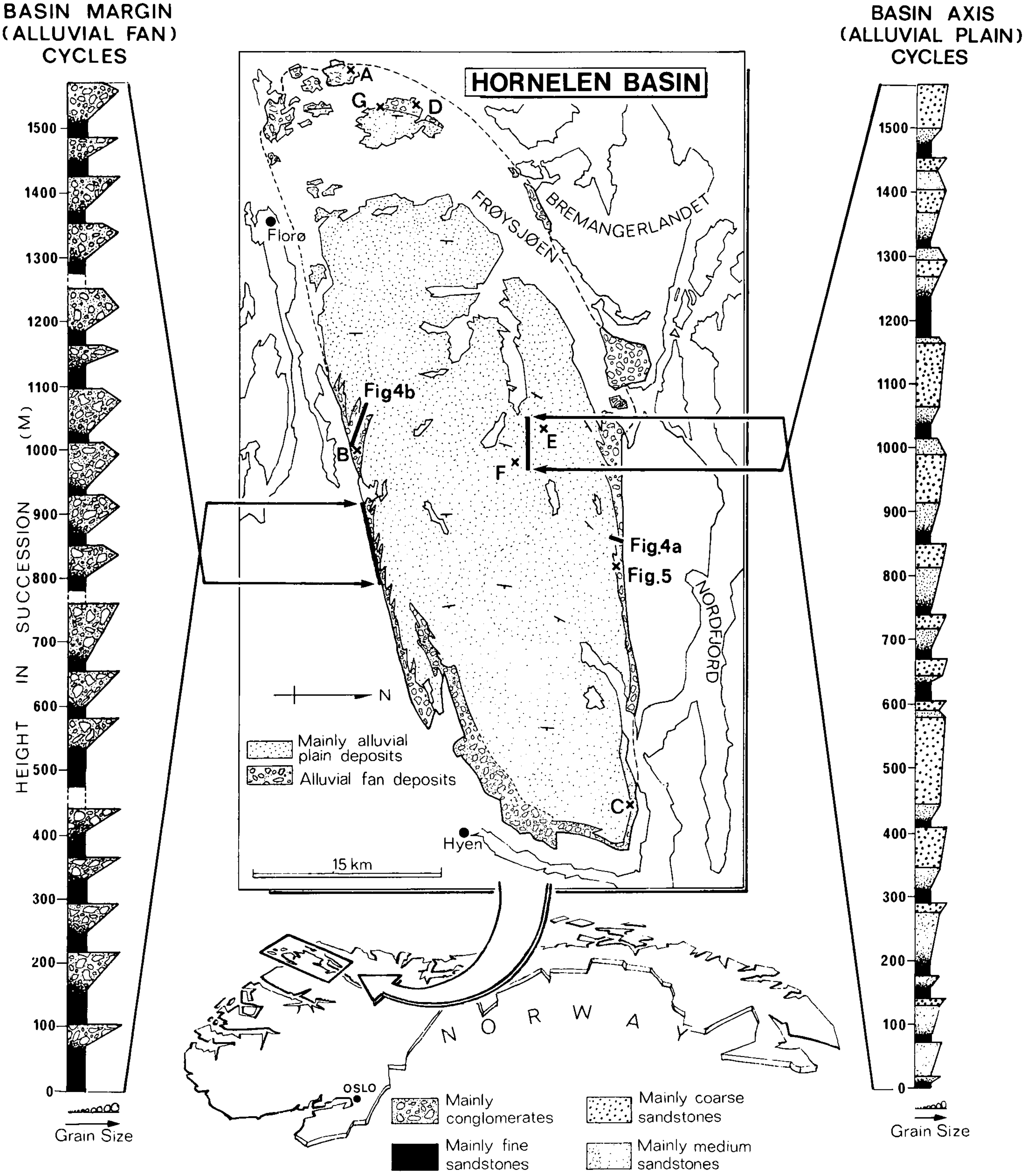


Figure 1. Simplified map of Hornelen Basin (after Kildal, 1970). Note the remarkable cyclicity permeating the 25-km-thick basin succession. Both axial and marginal deposits are dominated by coarsening-upward sequences. Lettering refers to the locations of sections shown on Figures 3 through 6. The bedding generally dips east at 20° to 40° but is subvertical on the northern margin.

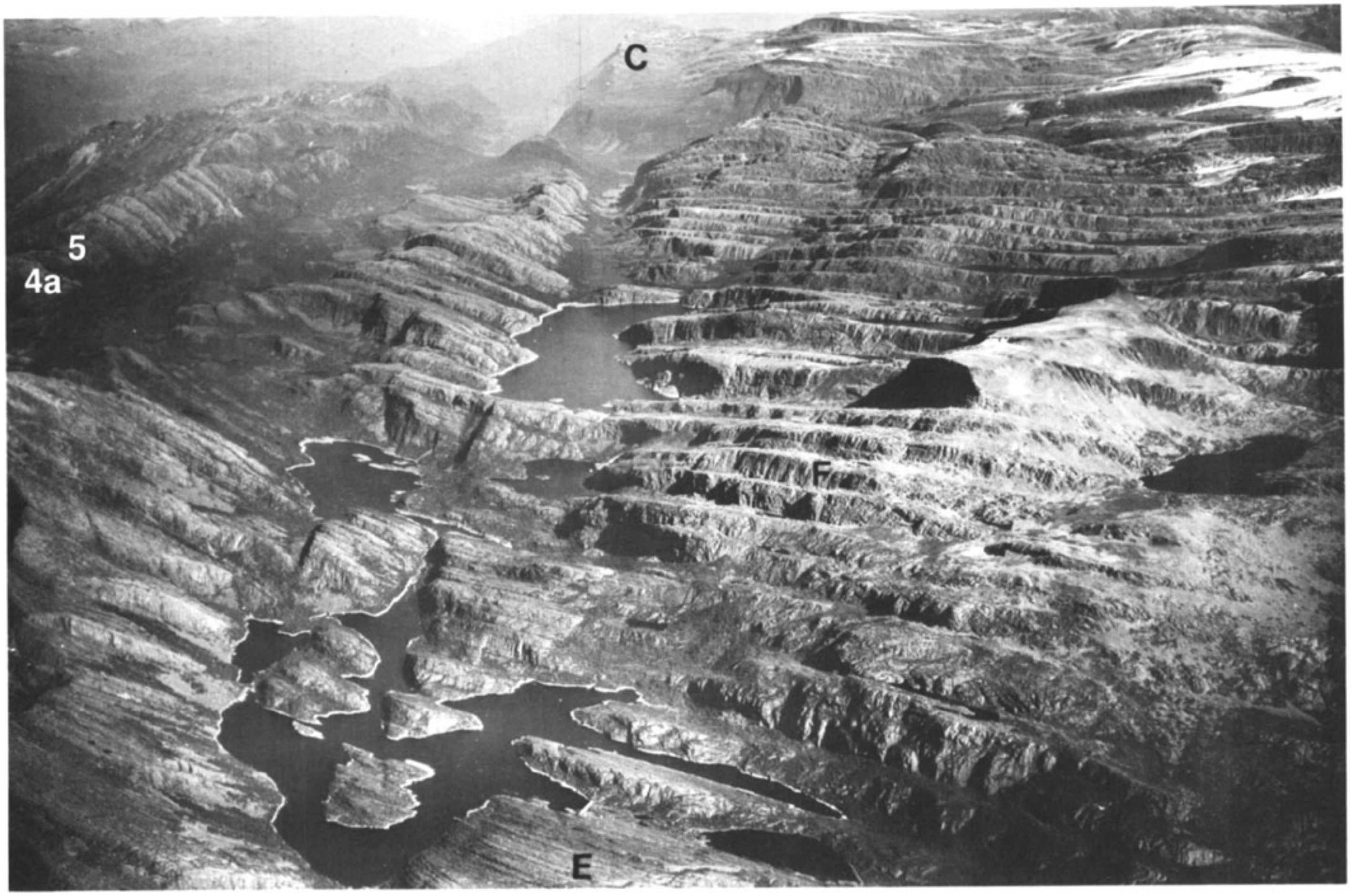


Figure 2. View eastward along part of the axial region of Hornelen Basin showing the basin-wide cyclicity. Scarps are of the order of 100 m high. Note the transition from fine-grained (immediate foreground) (Fig. 6, loc. E) to coarse-grained alluvial plain facies (middle distance) (Fig. 6, loc. F). Letters refer to Figures 3 through 6.

The two most striking features of the basin succession are the apparently enormous stratigraphic thickness (~ 25 km) (Kolderup, 1927; Bryhni, 1964a) and the presence of a prominent cyclicity through much of this (Figs. 1 and 2). We are particularly interested here in the latter feature. Superb exposure across the basin provides an unusual opportunity for examining both the sediments and the cyclicity, as it is traced through the various laterally equivalent facies.

We attempt to examine the cyclothems in both their marginal (alluvial fan sediments) and axial (alluvial plain sediments) development, but we discuss mainly the marginal facies, because as these are very coarse grained, they are likely to reflect the details of marginal tectonics more clearly.

MEASUREMENT OF CYCLOTHEMS

We use the terms "cyclothem" or "cycle" in the very general sense recommended by Duff and others (1967, p. 2). Because of the critical importance of the correct delimitation of cyclothems and the correct recognition of their internal trends, we make the following points concerning field measurements:

Maximum particle size and bed thickness measurements in conglomerates were made in the manner and for the reasons outlined by Bluck (1967). The plotted values of particle size represent a mean value of the ten largest clasts (after the omission of any "outsized" clasts) from an area over several metres on either side of the point of bed-thickness measurement. Bed-by-bed maximum particle size readings together with sandstone percent averages proved to be critical in the recognition of coarsening-upward trends within fan bodies and therefore also in the delimiting of fan cyclothems. In places where the uppermost fraction of a conglomerate sequence becomes finer grained, the cyclothem boundary was placed above this portion but immediately below the overlying fine-grained sandstones and siltstones.

In the sandstone succession of the basin axis region, cyclothems are less easy to define and have probably been previously identified incorrectly as fining upward (Bryhni, 1964c), presumably the simplest interpretation of a succession seen to consist of an apparent alternation of fine- and coarse-grained "members." Detailed measurements through numerous coarse "members" have since demonstrated that they are internally dominated by a coarsening upward and that there is usually a transition up from the underlying fine "member." The latter usually overlies the coarsest portion of an underlying sequence. This position of the cyclothem boundaries was further demonstrated when they were traced laterally into the bounding surfaces of well-defined marginal fan cyclothems.

MARGINAL SEQUENCES (ALLUVIAL FAN BODIES)

The marginal deposits are likely to have accumulated mainly on alluvial fans. This environment is suggested by the coarseness of the

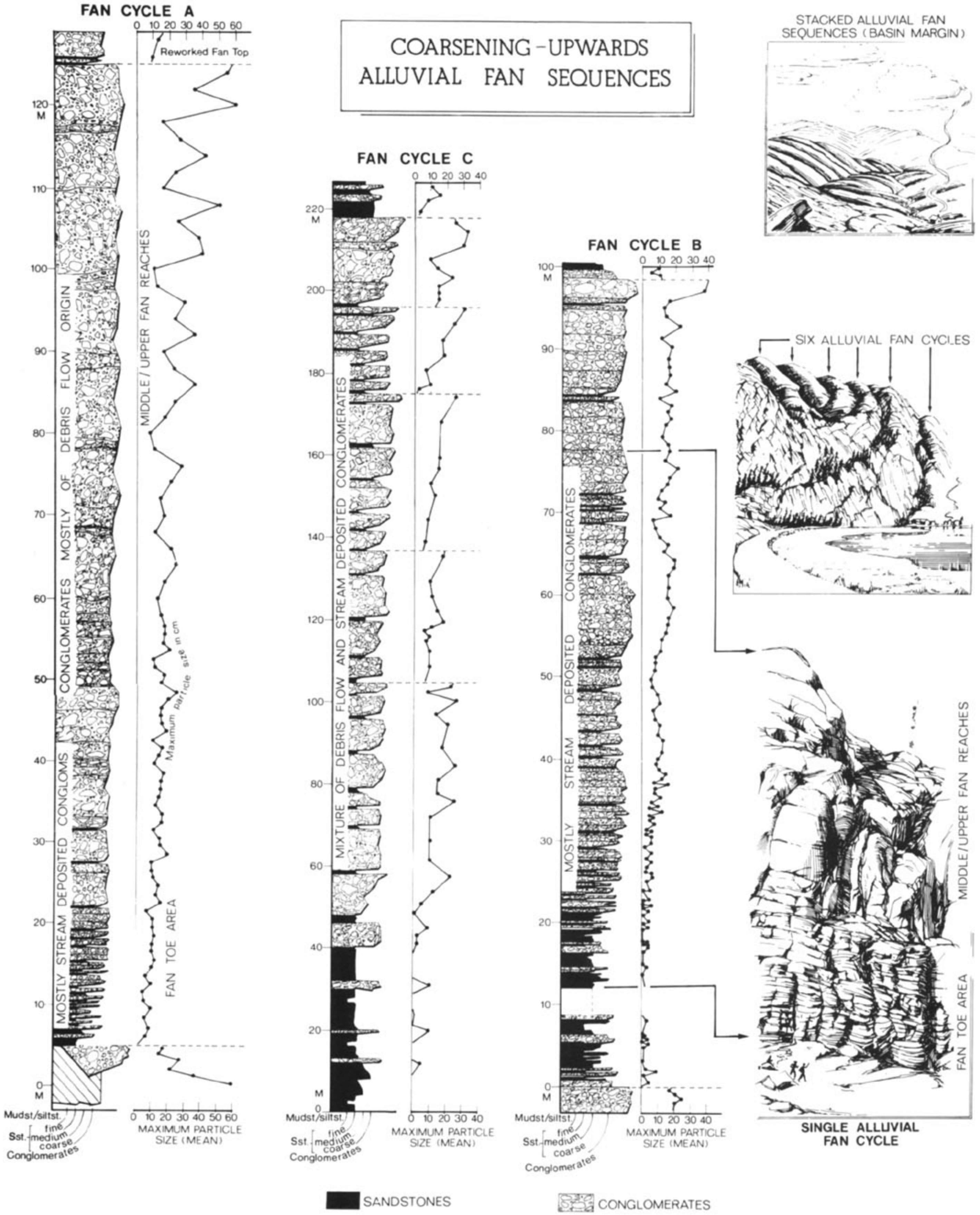


Figure 3. Some of the internal details of three alluvial fan sequences. Note the general coarsening upward as well as increasing maximum particle size upward. Profile C is clearly segmented into a number of coarsening-upward units.

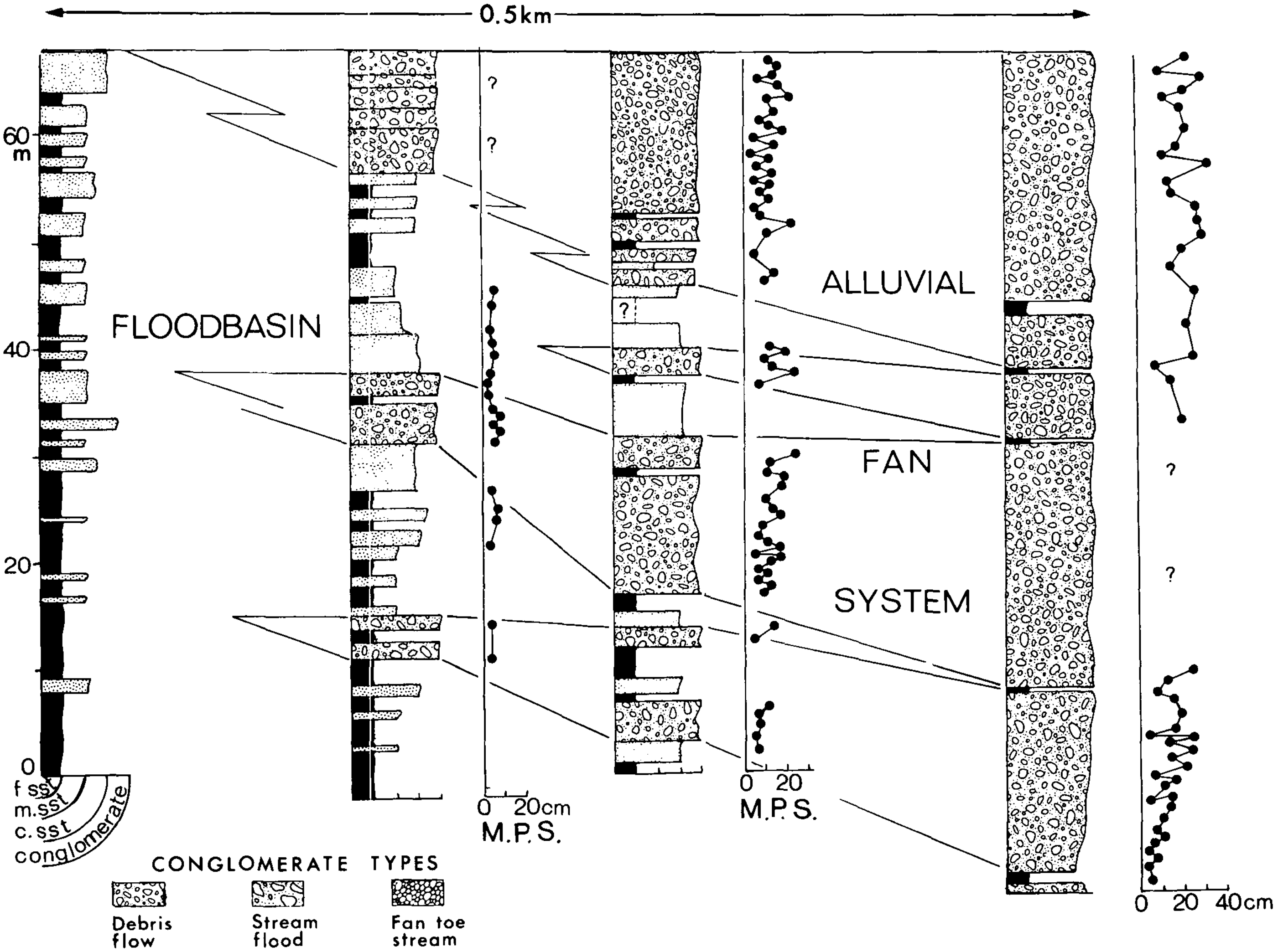


Figure 4a. Internal details of a composite, debris-flow–dominated alluvial fan wedge which is interfingering with floodbasin fines along the northern margin of Hornelen Basin. Note the progressive change in sediment coarseness as well as in maximum particle size (MPS) both distally and upward in the fan body.

sediments (Fig. 3), the wedge shape (in section) of the bodies (Fig. 4), progressive downfan decrease in maximum clast size throughout the wedge (Fig. 4), and frequent dominance of clasts from local "basement," evidence of subaerial exposure (for example, mudcracks, rainprints) and the paleocurrents which sometimes indicate a "fan-like" dispersal out from the basin margins. Some cyclothems in the marginal areas also include fine-grained sediments derived from the basin-axis floodplain system. This material sometimes wedges out before the margin is reached, but, when present, occupies the lowest part of the cyclothem (Figs. 3, 4).

The alluvial-fan deposits have been studied at three levels of organization. At the most general level, there are successions of the order of kilometres thick, which consist of stacked alluvial fan bodies, mostly of the same type. For example, successions of fan bodies of predominantly debris-flow deposits (Fig. 3, loc. A; Fig. 4a), of predominantly stream deposits (Fig. 3, loc. B; Fig. 4b), or of mixed types (Fig. 3, loc. C) have been identified along different marginal segments of the basin. Secondly, the general organization within individual fans is of interest. Along the southern margin of the basin, fan bodies (~5-km radius and 50 to 80 m thick in proximal reach) are highly asymmetric, dominated by coarsening and thickening-upward trends (Figs. 3, 4b), while those bodies along the northern margin are frequently of smaller radius (~1 km), thicker (100 to 200 m), and are less asymmetric (Fig. 4a). In the latter instances, however, a general coarsening upward can still be seen. In addition, individual fan sequences commonly consist of a number of subunits (10 to 25 m thick), and each of these also may be dominated by coarsening- and thickening-upward trends (Fig. 3, loc. C; Fig. 5). Finally, the sediments themselves, at bed or sedimentation-unit level, have been studied, and various types of debris-flow, mudflow, and streamflow deposits have been recognized.

Details of the various sediment facies at bed level are beyond the scope of the present discussions (see Maehle, 1975; Nilsen, 1975; Spinnangr, 1975) but will be treated in detail elsewhere. The ensuing discussion is concerned mainly with the second level of organization, because the individual, coarsening-upward fan body is believed to be the unit of major importance in the basin succession and is of tectonic significance.

Some 55 alluvial fan bodies along the margins of the basin have been examined. Of these, 90 percent show the following features:

(1) A general coarsening-upward, indicated by decreasing sandstone (discrete bed) percentage (Figs. 3, 4). (2) Coarsening upward of the conglomerates themselves as indicated by increasing

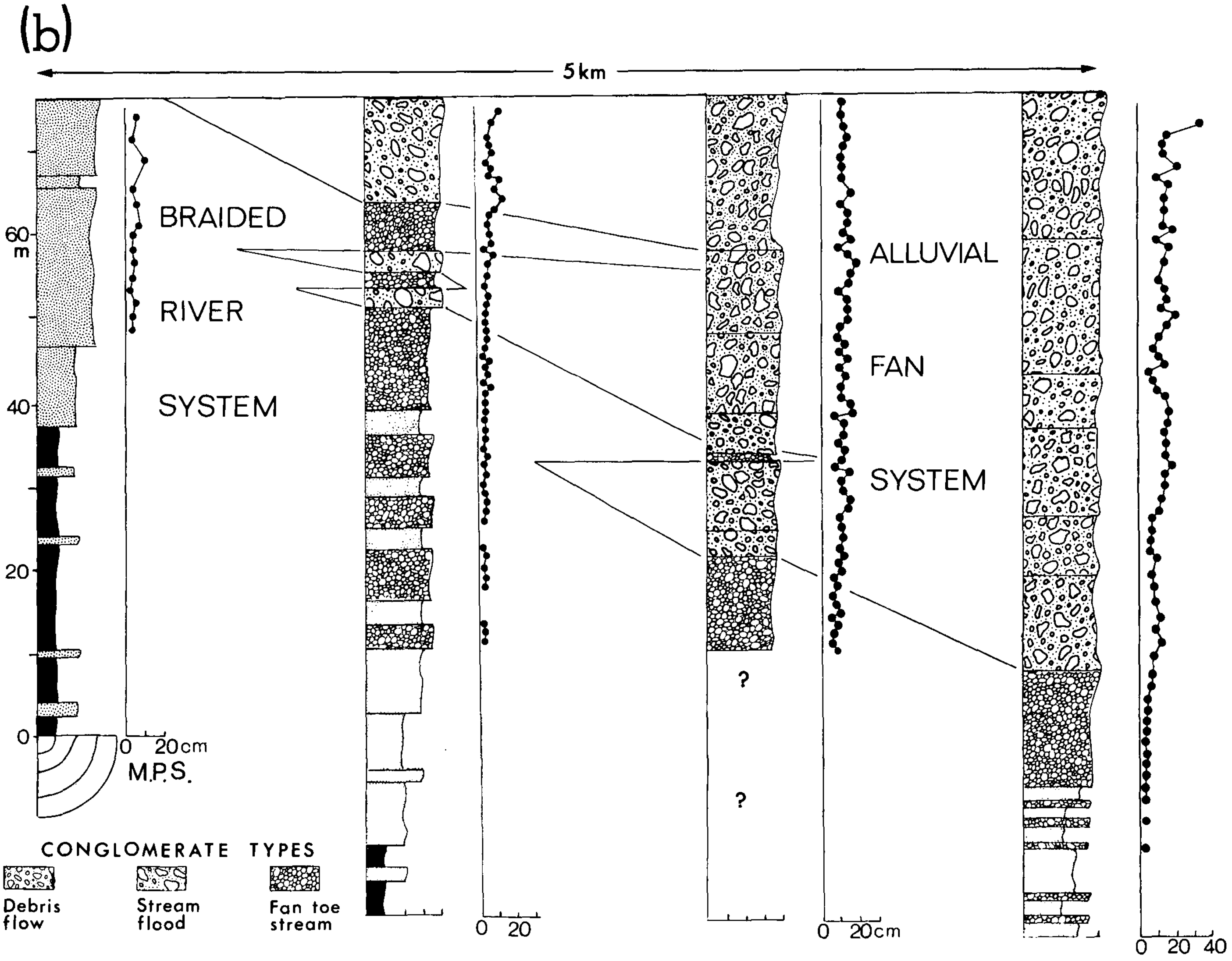


Figure 4b. **Internal details of a stream-dominated alluvial fan body on the southern margin of Hornelen Basin. Note the contrasts with the fan of Figure 4a in facies, fan radius, overall cross-sectional geometry, and downfan rate of change of MPS, despite the similar coarsening upward and fining outward. Legend as in Figure 4a.**

mean maximum clast size (Figs. 3, 4). (3) A general thickening-upward of conglomerate beds as implied from a positive bed thickness–maximum particle size relationship. (4) A sharp and apparently planar upper boundary to the fan body (Fig. 4). The coarsest fanglomerates are abruptly overlain by the finest alluvial plain sediments. (5) Lower boundary is gradational because there is a gradual coarsening upward from alluvial plain sandstones to the finest (distal) fanglomerates. This has resulted from a lateral interfingering of fan and alluvial plain sediments and from the gradual enlargement of fan radius through time so that the base of the fan body is now diachronous (Fig. 4).

The coarsening upward is not restricted to a particular sector of any fan body, and so the responsible mechanism is not a local one. The general grain-size and bed-thickness trends therefore suggest that successive dispersions on the fan surfaces were of increased competence and capacity. Moreover, because successive dispersions contained greater volumes of debris, individual fans had a characteristic history of radial enlargement. Because of fan-area–source-area relationships (Bull, 1964; Hooke, 1968), there is also implied an increasing drainage area with time.

The question arises as to the cause of the increased volume of debris shed onto the fans with time. In a Devonian piedmont situation, this may be attributed to time changes in relief, climate, or bedrock geology in the drainage area, probably in that order of importance (Blatt and others, 1972). Bedrock controls were probably unimportant because there are no significant vertical changes in pebble type in individual fan sequences. Of relief and climatic controls, the former was probably more important for the following reasons:

(1) Coarse-grained, conglomeratic fan sequences, each of the order of 100 m, were repeatedly built and stacked above each other. (2) The marginal fan cycles are notably asymmetric (Fig. 1); that is, they coarsen upward. As discussed below, this asymmetry is more easily explained by a lateral (tectonic) shifting of the locus of subsidence and sedimentation than by a climatic hypothesis. (3) The coarsening upward in the fan sequences appears to be independent of the dominant type of deposit from which the fans were built. Sequences dominated by debris-flow deposits, stream deposits, or mixtures of this show similar time trends (Fig. 3). Climatic change probably tends to alter the dominant depositional process during fan building (Lustig, 1965). (4) Hornelen Basin presently has prominent fault boundaries (Figs. 1 and 8), and subsidence was certainly a major control on the accumulation of 25 km of sediment within this relatively small area.

It is suggested that, in the areas adjacent to the basin margins, the effect of a relative subsidence of the basin floor was the creation of relief, increased drainage area in the new upland region and unstable slopes. It is further suggested that the main tectonic event is marked by the sharp planar top of any fan body, while the overlying coarsening-upward sequence records the gradual export of stored debris and the gradual building of the next fan outward in an attempt to re-establish an equilibrium profile across the basin margin. The coarsening upward itself simply records the tendency for relatively distal deposits to be overlaid by more proximal deposits through time, as the radius of the fan enlarges. Because the coarsening upward is a feature of the entire fan body, growth appears to have taken place fairly uniformly over the fan surface.

As regards the tectonic mechanism, it is of interest to speculate about the frequency or intensity of fault movement needed to produce a single coarsening-upward sequence. In fan sequences many times thicker than those here, it has been suggested that coarsening upward may have resulted from faulting with a history of progressively greater movements (Steel and Wilson, 1975). In the present case, with sequences of the order of 100 m, we suggest that several short-lived but intense movements along the same fault line may have been sufficient to begin and maintain continuous fan growth. It is possible that there was a lag between each tectonic event and the sedimentary response so that a uniform series of fault movements caused an accumulation and progressive storage of gravel, with a resultant gradual enlargement of fan size. If we assume that it is unrealistic to postulate a single fault scarp of the order of 50 to 100 m high, then it is tempting to correlate the subunits in many of the fan sequences with discrete episodes of fault movement. The segmented nature of many of the fan sequences is clear (Fig. 3, loc. C; Fig. 5), and in some fans, the subcycles show not only a coarsening upward but also a thickening upward of component beds (Fig. 5). Of course, these subcycles may have resulted from an autocyclic mechanism on the fan, such as from the natural intermittent lateral shifting of the main dispersal system. There are, however, two attributes of the subcycles which favor an origin from external events. First, they appear to have a sheet-like geometry which suggests that they represent a unit of accretion over most of the fan surface. In addition, in some areas of the basin, the subcyclicity appears to penetrate the alluvial plain facies beyond the fan toes. Secondly, in some segmented profiles, particularly along the northern margin, the base of each subcycle consists of fine-grained sandstones and siltstones derived from the basin-axis dispersal system and not from the fans themselves (Fig. 5). This feature again emphasizes that the subcyclicity is not simply an internal feature of the fan prism but penetrates from the marginal into the basin-axis facies.

The Hornelen type of fan sequence contrasts strongly with other described Devonian (Bluck, 1967) and Triassic (Steel, 1974) basin-margin fan sequences that are characterized by a fining upward. It is likely that such sequences, particularly if they are relatively thin, could have been generated either against basin margins where the rate of subsidence was minimal (and sourceward scarp retreat was important) or across basin margins which were actively expanding by a sourceward shifting of the locus of faulting and subsidence (Steel and Wilson, 1975; Steel and others, 1975).

AXIAL SEQUENCES (ALLUVIAL-PLAIN SAND BODIES)

Approximately 90 percent (by volume) of the sediments in Hornelen Basin are sandstones which accumulated from a westward-flowing fluvial system (Figs. 1, 8b). They form a variety of facies, the sum of which may be loosely referred to as an alluvial-plain association. Detailed study of these sediments is yet at

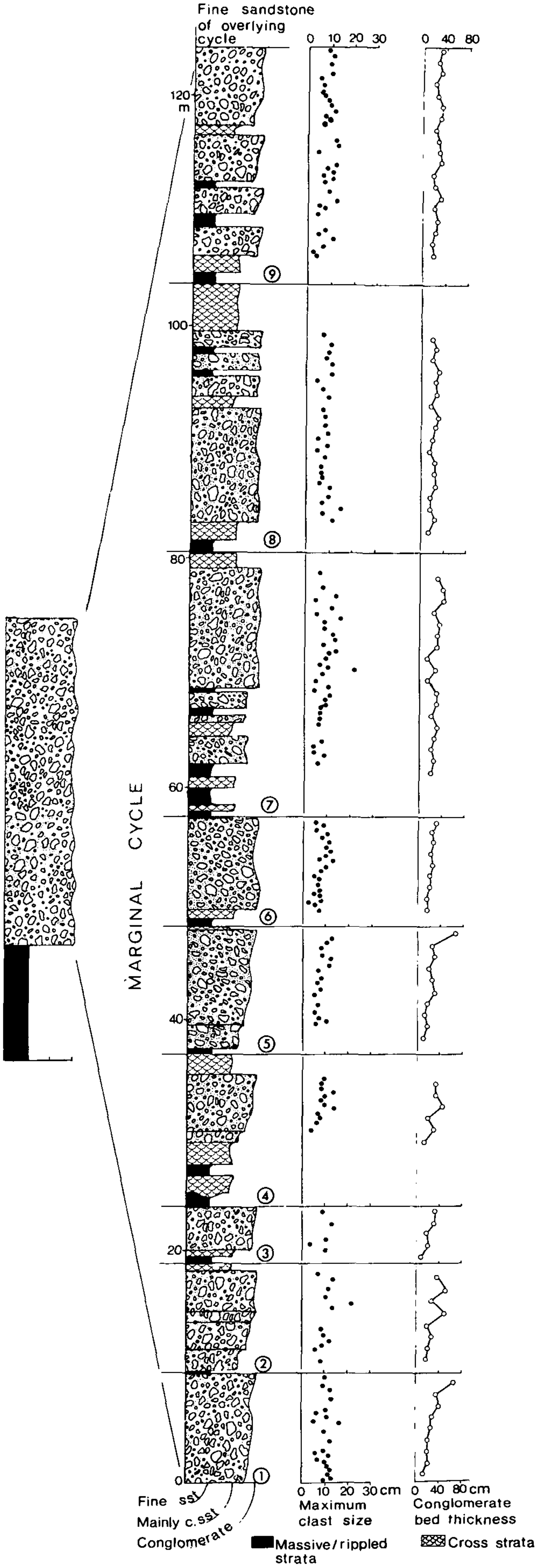
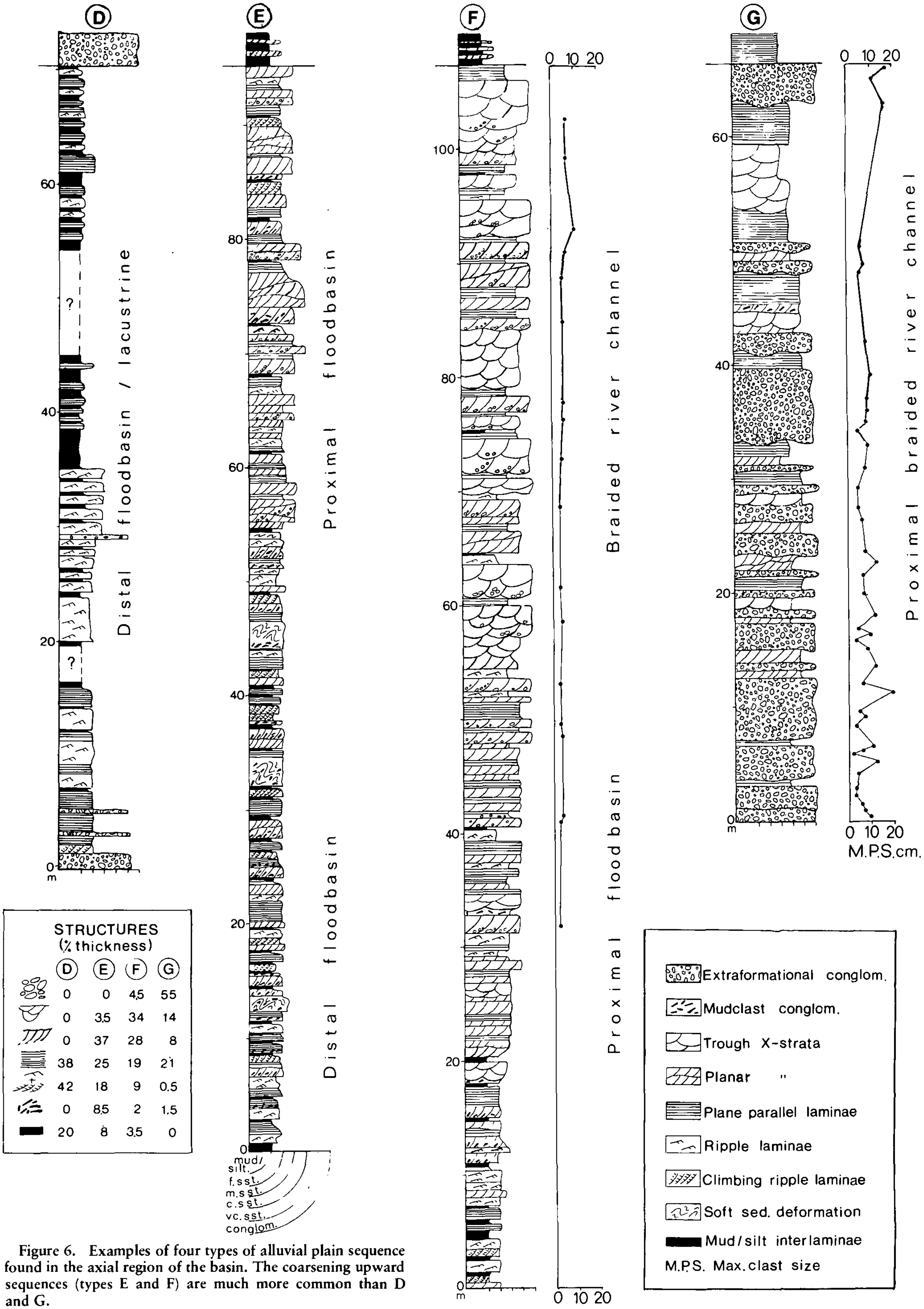


Figure 5. Details of the coarsening upward and thickening upward within subunits in the fanglomerate portion of a cyclothem on the northern margin. The fine sandstone at the base of the subunits is of floodbasin origin and not derived from the fans.



STRUCTURES
(% thickness)

	D	E	F	G
⁘	0	0	4.5	55
◡	0	3.5	34	14
⫽	0	37	28	8
☰	38	25	19	21
∼	42	18	9	0.5
⋰	0	8.5	2	1.5
▬	20	8	3.5	0

Figure 6. Examples of four types of alluvial plain sequence found in the axial region of the basin. The coarsening upward sequences (types E and F) are much more common than D and G.

a preliminary stage, but a number of facies of progressively more distal aspect (progressively finer grained) have been recognized. It is assumed that sequences with abundant polymict conglomerates are most proximal while those with greater amounts of ripple lamination and mudclast-conglomerate – mudstone strata are more distal (Fig. 6). If these criteria are correct, it is of additional interest to note that both plane parallel lamination and planar cross-stratification show some increase in amount distally while trough cross-strata decrease (see summary of structures, Fig. 6; see also Smith, 1970).

Like the alluvial fan deposits, these facies sequences are vertically repeated many times in different parts of the basin (Fig. 1). Cycle thickness varies from 70 to 140 m. Most of the sequences exhibit a coarsening upward which reflects transition from relatively distal to relatively proximal parts of the alluvial-plain system (Fig. 6, profiles E and F). On the other hand, the few outcropping examples of the most proximal (Fig. 6, profile G) and the most distal sequences (Fig. 6, profile D), which are usually relatively thin, appear to show no similar vertical organization. Cycles containing these end-member types represent less than 5 percent of the total in the basin.

It has not been possible to examine a single cycle for more than several kilometres longitudinally in the basin, partly because of inaccessibility and because the succession has an eastward tectonic dip parallel to the main axial paleoflow and toward the proximal reaches. Therefore no single cycle has a demonstrable sourceward facies change such as that shown by the profiles D through G in Figure 6. However, a great number of cyclothems can be examined vertically; these do show a range of variation typified by these sequences and suggest that any one cyclothem has the geometry and facies differentiation approximating that shown in Figure 7a. In addition, individual cyclothems can be examined laterally and demonstrable facies changes from braided river channel deposits into floodbasin deposits are consistent with the proposed model (Fig. 7b). Examination of aerial photographs of the basin suggest that axial cyclothems may have a minimum east-west extent of 10 to 12 km.

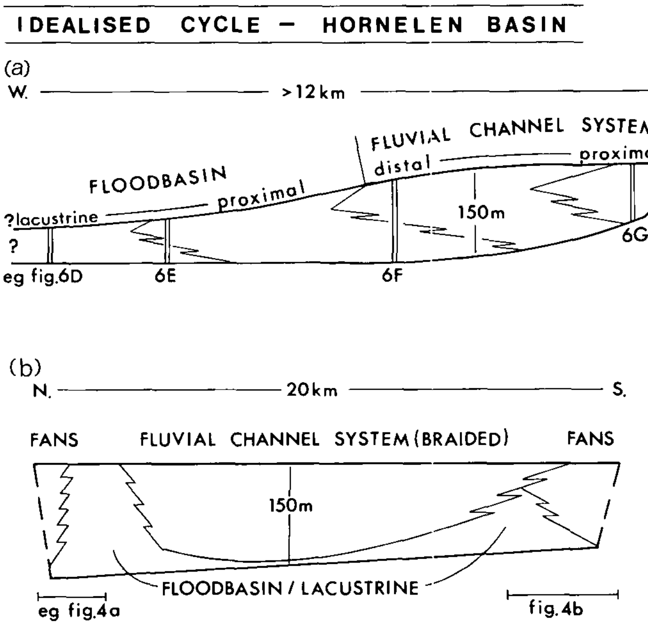


Figure 7. Suggested longitudinal and lateral geometry and facies variation in the Hornelen Basin cycles. Section b can be observed; section a is hypothetical.

The general coarsening upward of most of the alluvial plain cyclothems is also interpreted in terms of a general (westward) progradation of the basin-axis system, so that within a single cyclothem, the deposits of, for example, proximal channel reaches gradually encroached on distal reaches. The apparent arrangement of floodbasin-lacustrine deposits both laterally and distally equivalent to the deposits of the main channel system suggests a closed-basin situation.

Any individual, axially transported alluvial-plain sequence can be traced laterally into a marginal alluvial fan sequence. The axial cyclicity is, therefore, not independent of that developed marginally and, for reasons already discussed, we suggest that cyclothems in their entire width (basin-wide) are the product of discrete episodes of basin subsidence. The basin infill consists of more than 150 cyclothems, implying a similar number of major episodes of alluvial-plain progradation and probably the same number of major episodes of basin subsidence.

The alluvial plain cyclothems also often consist of a number of coarsening-upward subcycles, of the same order of size as those in the fan sequences (Fig. 6, profile F). Their development here, however, is less easily argued as attributable to allocyclic mechanism, although in certain well-exposed areas, they can be "walked-out" into subunits on the fans.

FAULTING, SUBSIDENCE, AND SEDIMENTATION

In the previous sections, the individual cyclothem has been examined, and the development of facies variation within it has been briefly discussed. The evidence suggests that the development of a typical 100-m-thick cyclothem represented aggrading base-level conditions in the basin in response to a lowering of its floor. Further, internal details of cyclothems suggest that the amplitude of single subsidence events was commonly of the order of 10 to 25 m, as reflected by individual cyclothems being composed of six to ten subunits.

The question then arises as to the tectonic significance of the boundaries between cyclothems as compared to those between subcyclothems. We suggest, because of the spatial relationship of adjacent subcyclothems (in fan sequences), that the latter boundaries separate intervals during which units of sediment were vertically stacked — that is, the group of subunits within a single cyclothem originated from approximately the same focus. On the other hand, the cyclothem boundaries appear to represent intervals during which there was an important eastward shift in the locus of both marginal and axial dispersal systems.

Bryhni (1964a) suspected that the cyclothems overlap each other eastward in Hornelen Basin; he noted that a series of progressively younger alluvial fan bodies on the southern margin appeared to be displaced successively eastward. Further examination of this and other similar areas suggest to us that the amount of overlap of successive cyclothems is commonly less than 0.25 km. In addition to this evidence, a periodic, rapid eastward shift of the main locus of subsidence could account for the remarkable planar tops of cyclothems and for their strong asymmetry. A discontinuous eastward migration of the marginal fans and of the proximal reaches of the axial fluvial system would result in a more exaggerated grain-size asymmetry in the cycles than would be the case if they were stacked vertically. During the eastward shifting of the locus of sedimentation, it might be expected that the underlying sequence should be locally tilted eastward. In only one area has a slight unconformity, with this sense, been recorded at the base of a cyclothem.

The validity of the above model for Hornelen Basin development may also be argued indirectly, from the enormous stratigraphic thickness of the basin succession. The lack of a significantly higher

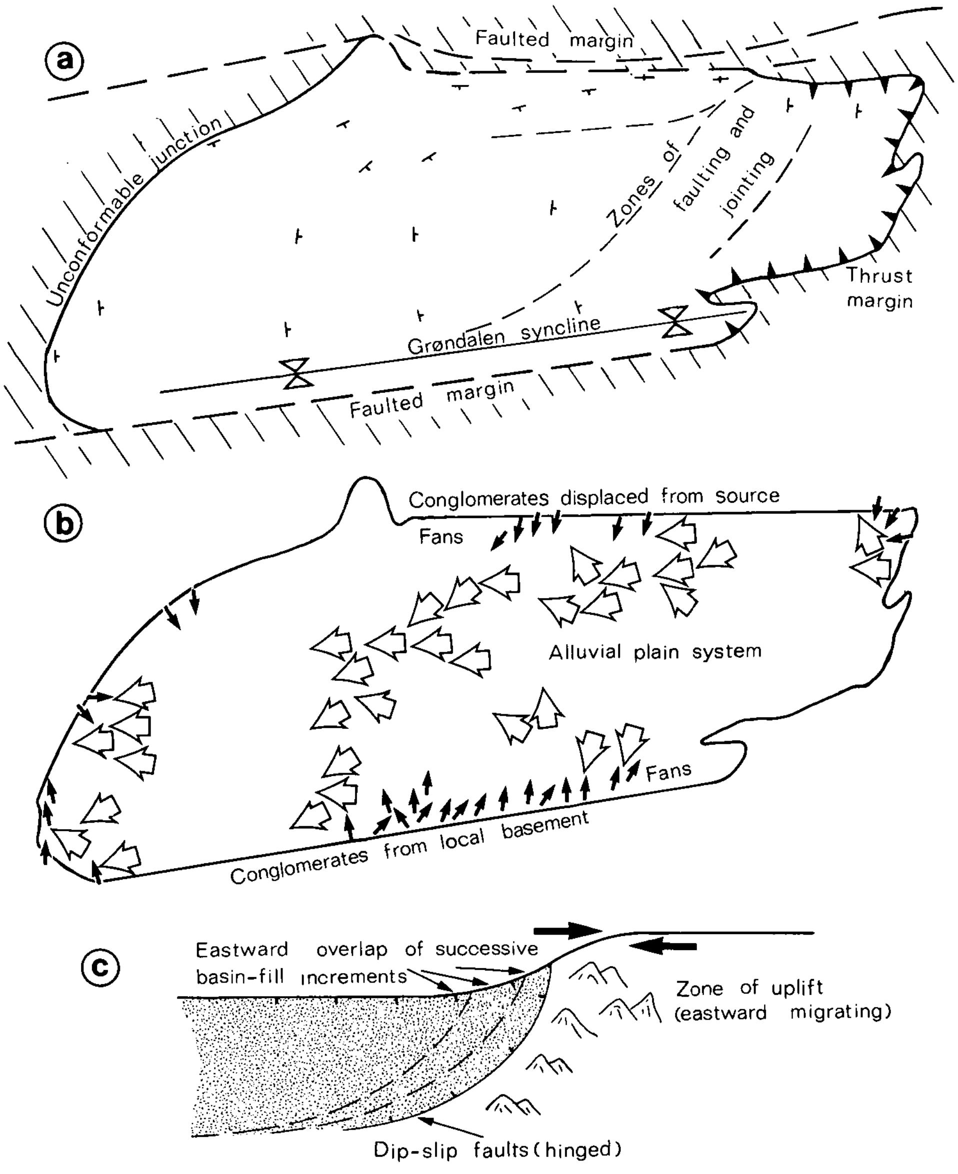


Figure 8. a. Some of the main structural features of Hornelen Basin; b. paleocurrent systems (solid arrows are marginal fanglomerate dispersal; open arrows are axial sandstone system dispersal); c. a speculative model of basin development along the southern flank of a right-slip wrench system.

degree of metamorphism at the base of the pile than at the top (Bryhni, 1964b) suggests that the basin was not 25 km deep. Assuming a simple repetition of the type of cyclothem shown in Figure 7, present estimates of the minimum east-west extent of individual cyclothems (12 km) and of the amount of eastward overlap between adjacent cyclothems (0.25 km), together with an average cycle thickness of 120 m, suggest that the basement may not have been deeper than 6 km below the surface of the basin.

The argument may be taken a stage further. A basin in which the overall rate of vertical subsidence was less than the overall rate of lateral expansion could be described as one developing under the control of a wrench fault system. Examples of basins developing in response to wrench fault systems have been figured and discussed by Crowell (1974), mainly in terms of pullapart basins formed at releasing double bends or sag basins formed adjacent to rising uplands on restraining double bends. In the case of Hornelen Basin, the observed eastward overlap of successive basin-fill increments does not in itself necessarily imply that basin development was controlled by strike-slip faulting, but the following features (Fig. 8) are consistent with such a notion, and they suggest that the basin may have formed on the southern flank of a right-slip (oblique) fault system approximately along the present line of Nordfjord:

1. Because of the predominantly strike-slip movement and dip-slip movement along the northern and southern margins, respectively, of the model basin (Fig. 8c), it is predicted that a reasonable correspondance exists between conglomeratic pebble composition and adjacent "basement" lithology across the southern margin, but that anomalies exist across the northern margin. These predictions are partially confirmed where easily identified augen-gneiss pebbles in conglomerates along the western part of the northern margin conglomeratic belt now lie adjacent to schists, with the parent augen-gneiss displaced eastward (right-slip) by more than 5 to 10 km. In younger conglomerates along the same margin, gabbroic and granodioritic clasts can be less easily matched with basement and may imply considerably great right-slip movement. On the other hand, along the central part of the southern margin of the

basin, a change from quartzite to gneiss as dominant pebble type appears to correspond fairly well with a similar change in adjacent "basement" lithology (Fig. 8b).

2. The faulted southern margin of the model basin is less regular and linear than the northern margin because the development of the southern margin is dependent on the coalescence of a number of hinged, curved southwest-northeast dip-slip faults (Fig. 8c). The latter define the southern boundary of the area of sag caused by the strike-slip movement of basement blocks against each other along a restrictive double bend (see Fig. 4 in Crowell, 1974). The southeastern end of Hornelen Basin, as defined now by the fringing fanglomerates, appears to have resulted from at least two, curved, subparallel fault systems (Fig. 1). In addition, there are prominent, curved northeast-southwest zones of jointing presently cutting the basin, possibly reflecting reactivated basement faulting (Fig. 8a).

3. The facts that the bulk of Hornelen Basin sediments are sandsized and that these filled the basin longitudinally from its east end (Fig. 8b) are reasonably consistent with the strike-slip fault model. In contrast, Solund Basin, of similar size and subparallel to Hornelen Basin but lying some 60 km to the south, is filled with 5 km of coarse conglomerates which were dispersed laterally into the basin. This grain size and mode of filling is more typical of a rift basin, dominated by dip-slip tectonics (Steel, 1976).

CONCLUSIONS

The basic response to vertical movement of Hornelen Basin floor is deduced to have been the creation of marginal relief, gradually increasing sediment discharge into the basin, and the progradation of sedimentary bodies in which a characteristic coarsening-upward sequence was generated.

The major bodies produced by such a period of subsidence are composite, being constructed of marginally dispersed fanglomerates and longitudinally dispersed fluvial sandstones, but they are basin-wide and commonly of the order of 100 m thick. These major bodies are composed, in turn, of thinner tabular units, also coarsening upward, of the order of 10 to 25 m, which are believed to reflect more closely the maximum amplitude of individual phases of subsidence.

The main significance of the 100-m unit is that this vertical interval represents the period after which the locus of subsidence suffered a rapid lateral migration, commonly of the order of 0.25 km. This periodic eastward migration caused an overlap of the basement and the generation of a stratigraphic thickness of some 25 km in the basin.

A possible model for the development of this basin sequence with its spectacular cyclicity is one involving discontinuous strike-slip movement along a major right-slip wrench system.

ACKNOWLEDGMENTS

We thank our colleagues at the Geological Institute (Department A) for stimulating discussions about Hornelen Basin. Professors Crowell (California), Bluck (Glasgow), Sturt and Kvale (Bergen), and Tesseyre (Wroclaw) read the manuscript and suggested improvements. We are also grateful to Professor A. Whiteman, who initiated the West Norway Devonian Project, and to Norges Teknisk-Naturvitenskapelige Forskningsråd, who largely financed it.

REFERENCES CITED

Blatt, H., Middleton, G., and Murray, R., 1972, Origin of sedimentary rocks: Englewood Cliffs, New Jersey, Prentice Hall, 634 p.

Bluck, B. J., 1967, Deposition of some Upper Old Red Sandstone in the Clyde area: A study in the significance of bedding: Scottish Jour. Geology, v. 3, p. 139–167.

Bryhni, I., 1964a, Migrating basins on the Old Red Continent: Nature, v. 202, p. 284–285.

——1964b, Relasjonen mellom senkaledonsk tektonikk og sedimentasjon ved Hornelens og Håsteinens devon: Norges Geol. Undersøkelse, v. 223, p. 10–25.

——1964c, Sediment structures in the Hornelen series: Norsk Geol. Tiddskr., v. 44, p. 486–488.

Bull, W. B., 1964, Alluvial fans and near surface subsidence in West Fresno, California: U.S. Geol. Survey Prof. Paper 437A, 71 p.

——1968, Alluvial fans: Jour. Geol. Education, v. 16, p. 101–106.

Crowell, J. C., 1974, Origin of late Cenozoic basins in southern California, *in* Dickinson, W. R., ed., Tectonics and sedimentation: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 22, p. 190–204.

Duff, P.McL.D., Hallam, A., and Walton, E. K., 1967, Cyclic sedimentation: Amsterdam, Elsevier, 280 p.

Hooke, R.L.B., 1968, Steady-state relationships on arid region alluvial fans in closed basins: Am. Jour. Sci., v. 266, p. 609–629.

Kildal, E. S., 1970, Geologisk kart over Norge, berggrunn kart, 1:250,000: Norsk Utgave, Norges Geol. Undersøkelse.

Kolderup, C. F., 1927, Hornelens Devonfelt: Bergens Mus. Arb. 1926, Naturvidensk. Raekke nr. 6.

Lustig, L. K., 1965, Clastic sedimentation in Deep Springs Valley, California: U.S. Geol. Survey, Prof. Paper 35F, 131 p.

Maehle, S., 1975, Devonian conglomerate-sandstone facies relationships and their palaeogeographic importance along the margin of Hornelen Basin, between Storevann and Grøndalen, Sunnfjord [Cand. Real thesis]: Bergen, Norway, Univ. Bergen, 163 p.

Nilsen, H. R., 1975, Sedimentological studies along the central part of the southern margin (Haukå-Storevatn) of Hornelen Devonian basin, western Norway [Cand. Real thesis]: Bergen, Norway, Univ. Bergen, 223 p.

Nilsen, T. H., 1968, The relationship of sedimentation to tectonics in the Solund area of southwestern Norway: Norges Geol. Undersøkelse, v. 259, 108 p.

Spinnangr, Å., 1975, Some sedimentary and stratigraphic studies of the Devonian strata across the western part of Hornelen Basin, Western Norway [Cand. Real thesis]; Bergen, Norway, Univ. Bergen, 247 p.

Skjerlie, F. J., 1971, Sedimentasjon og tektonisk utvikling i Kvamshestens devonfelt, Vest-Norge: Norges Geol. Undersøkelse, v. 270, p. 77–108.

Smith, N. D., 1970, The braided stream depositional environment: Comparison of the Platte River with some Silurian clastic rocks, north-central Appalachians: Geol. Soc. America Bull., v. 81, p. 2993–3014.

Steel, R. J., 1974, New Red Sandstone floodplain and piedmont sedimentation in the Hebridean province, Scotland: Jour. Sed. Petrology, v. 44, p. 336–357.

——1976, Devonian basins of western Norway — Sedimentary response to tectonism and varying tectonic context: Tectonophysics, v. 36, p. 207–224.

Steel, R. J., and Wilson, A. C., 1975, Sedimentation and tectonism (?Permo-Triassic) on the margin of the North Minch Basin: Geol. Soc. London Jour., v. 131, p. 183–202.

Steel, R. J., Nicholson, R. N., and Kalander, L. K., 1975, Triassic sedimentation and palaeogeography in central Skye: Scottish Jour. Geology, v. 11, p. 1–13.

Manuscript Received by the Society December 8, 1975
Revised Manuscript Received July 10, 1976
Manuscript Accepted September 2, 1976