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Tectonics and sedimentation in the hangingwall of a major extensional detachment: the Devonian Kvamshesten Basin, western Norway

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ABSTRACT

The Middle Devonian Kvamshesten Basin in western Norway is a late-orogenic basin situated in the hangingwall of the regional extensional Nordfjord–Sogn Detachment Zone. The basin is folded into a syncline with the axis subparallel to the ductile lineations in the detachment zone. The structural and stratigraphic development of the Kvamshesten Basin indicates that the basin history is more complex than hitherto recognized. The parallelism stated by previous workers between mylonitic lineation below the basin and intrabasinal fold axes is only partly reflected in the configuration of sedimentary units and in the time-relations between deposits on opposing basin margins. The basin shows a pronounced asymmetry in the organization and timing of sedimentary facies units. The present northern basin margin was characterized by bypass or erosion at the earliest stage of basin formation, but was subsequently onlapped and eventually overlain by fanglomerates and sandstones organized in well-defined coarsening-upwards successions. The oldest and thickest depositional units are situated along the present southern basin margin. This as well as onlap relations towards basement at low stratigraphic level indicates a significant component of southwards tilt of the basin floor during the earliest stages of deposition. The inferred south-eastwards tilt was most likely produced by north-westwards extension during early stages of basin formation. Synsedimentary intrabasinal faults show that at high stratigraphic levels, the basin was extending in an E–W as well as a N–S direction. Thus, the basin records an anticlockwise rotation of the syndepositional strain field. In addition, our observations indicate that shortening normal to the extension direction cannot have been both syndepositional and continuous, as suggested by previous authors. Through most of its history, the basin was controlled by a listric, ramp-flat low-angle fault that developed into a scoop shape or was flanked by transfer faults. The basin-controlling fault was rooted in the extensional mylonite zone. Sedimentation was accompanied by formation of a NE- to N-trending extensional rollover fold pair, evidenced by thickness variations in the marginal fan complexes, onlap relations towards basement and the fanning wedge geometry displayed by the Devonian strata. Further E–W extension was accompanied by N–S shortening, resulting in extension-parallel folds and thrusts that mainly post-date the preserved basin stratigraphy. During shortening, conjugate extensional faults were rotated to steeper dips on the flanks of a basin-wide syncline and re-activated as strike-slip faults. The present scoop-shaped, low-angle Dalsfjord fault cross-cut the folded basin and juxtaposed it against the extensional mylonites in the footwall of the Nordfjord–Sogn detachment. Much of this juxtaposition may post-date sedimentation in the preserved parts of the basin.

Basinal asymmetry as well as variations in this asymmetry on a regional scale may be explained by the Kvamshesten and other Devonian basins in western Norway developing in a strain regime affected by large-scale sinistral strike-slip subparallel to the Caledonian orogen.

INTRODUCTION

Late-orogenic extension of overthickened crust has been described from ancient as well as modern orogens (e.g. Burchfiel & Royden, 1985; Séranne & Séguret, 1987; Dewey, 1988; Platt & Vissers, 1989; Jolivet *et al.*, 1994; Hartz & Andresen, 1995; Andersen & Jamtveit, 1990; Dewey *et al.*, 1993). While considerable advance has been made on the processes of detachment faulting and on the exhumation of deep crustal rocks, comparably few studies have focused directly on the late-orogenic extensional basins. The Devonian Kvamshesten Basin in western Norway is a late-orogenic supradetachment basin situated on the remains of the Caledonian mountain belt. We have mapped the Kvamshesten Basin in terms of contact relationships, sedimentology and structure to test recent conceptual models of late-orogenic extension and basin formation. The structural and sedimentological observations described below may serve as an example of the complexity encountered in late-orogenic basins. We think that in the present case, this complexity cannot be explained by continuous dip-slip extension on one low-angle normal fault.

The Devonian basins of western Norway

The Devonian basins of western Norway (Fig. 1) are regarded as classic study areas for tectonically controlled sedimentation (e.g. Bryhni, 1964a,b; Steel *et al.*, 1977; Steel & Gloppen, 1980; Byörlykke, 1983; Roberts, 1983). The documentation of low-angle extensional detachment faults and shear zones in the Sogn–Nordfjord area (Hossack, 1984; Norton, 1986, 1987; Séranne & Séguret, 1987) provided a new tectonic framework for western Norway. The Devonian basins are currently interpreted as products of the late-orogenic extension of the Caledonian mountain belt (Seguret *et al.*, 1989; Andersen & Jamtveit, 1990; Chauvet & Seranne, 1994). The basins are situated in the hangingwall of a regional extensional detachment zone (Andersen & Jamtveit, 1990) (Fig. 1). The detachment zone comprises up to 2 km of extensional mylonites that separate the eclogite-bearing Western Gneiss Region (WGR) in the footwall from Caledonian allochthon and Devonian basins in the hangingwall. The extensional mylonites carry a W- to WNW-plunging lineation and record a minimum of 40 km of ductile, top-to-the-W displacement that partly controlled exhumation of the Caledonian (Kullerud *et al.*, 1986) eclogites of the WGR (Andersen & Jamtveit, 1990; Hveding, 1992; Andersen *et al.*, 1994). ^{40}Ar/^{39}Ar cooling ages from amphibole and white mica in the footwall of the detachment zone cluster in the Early to Middle Devonian (Chauvet *et al.*, 1992; Berry *et al.*, 1995). Based on plant and fish fossils, the Devonian basins have been assigned Middle Devonian ages (Kolderup, 1916, 1921; Jarvik, 1949). Thus, ductile extensional shearing is usually taken to be roughly contemporaneous with Devonian sedimentation. Along their western margins, the Devonian basins are unconformable upon their depositional substrate of Precambrian and Caledonian rocks (Bryhni & Skjerlie, 1975). The eastern margins of the Devonian basins comprise brittle, undulating low-angle normal faults (Hossack, 1984; Norton, 1986, 1987; Séranne & Séguret, 1987). In the case of the Hornelen Basin, the southern and northern basin margins comprise steep, brittle strike-slip faults that cross-cut the detachment at the eastern basin margin (Norton, 1986; Torsvik *et al.*, 1988; Andersen *et al.*, 1997). The tectonostratigraphy described above is folded in large-scale, E–W-trending folds with axes roughly parallel with the ductile lineation in the detachment mylonites below. The Devonian basins and their depositional substrate crop out in the synforms, while the high-pressure rocks of the WGR crop out in the antiforms between the basins. Chauvet & Seranne (1994) described the folds as extension-parallel and argued that they were synsedimentary with respect to the Middle Devonian basins. Palaeomagnetic data, however, indicate that the folds are Late Devonian or Early Carboniferous in age (Torsvik *et al.*, 1986). An increasing amount of evidence from palaeomagnetic studies as well as from ^{40}Ar/^{39}Ar dating (Torsvik *et al.*, 1986, 1992; Eide *et al.*, 1997) indicate that the crustal section exposed in western Norway experienced deformation that is young with respect to the Devonian basins. Thus, some of the structures that bound the Devonian basins may entirely post-date basin formation and be Late Devonian, Permian or even Mesozoic in age (Torsvik *et al.*, 1988, 1992). In our view, these observations highlight the importance of a thorough re-investigation of the Devonian basins.

The Kvamshesten Basin – scope of the present study

The Kvamshesten Basin (Fig. 2) sits in the hangingwall of the Dalsfjord fault, a W-plunging, scoop-shaped detachment fault that separates the Devonian basin and its depositional substrate from extensional mylonites and the WGR (Fig. 3). The Dalsfjord fault constitutes the basin's present eastern, northern and southern margins, and experienced slip in Permian as well as Mesozoic times (Torsvik *et al.*, 1992). The Middle Devonian unconformity beneath the Kvamshesten Basin is exposed for more than 15 km. The well-exposed basin fill comprises roughly equal amounts of conglomerates and sandstones. The Kvamshesten Basin is thus well-suited for investigations of the basin floor topography, as well as of the relations between coarse- and fine-grained sedimentary units. In this paper the following points are highlighted.

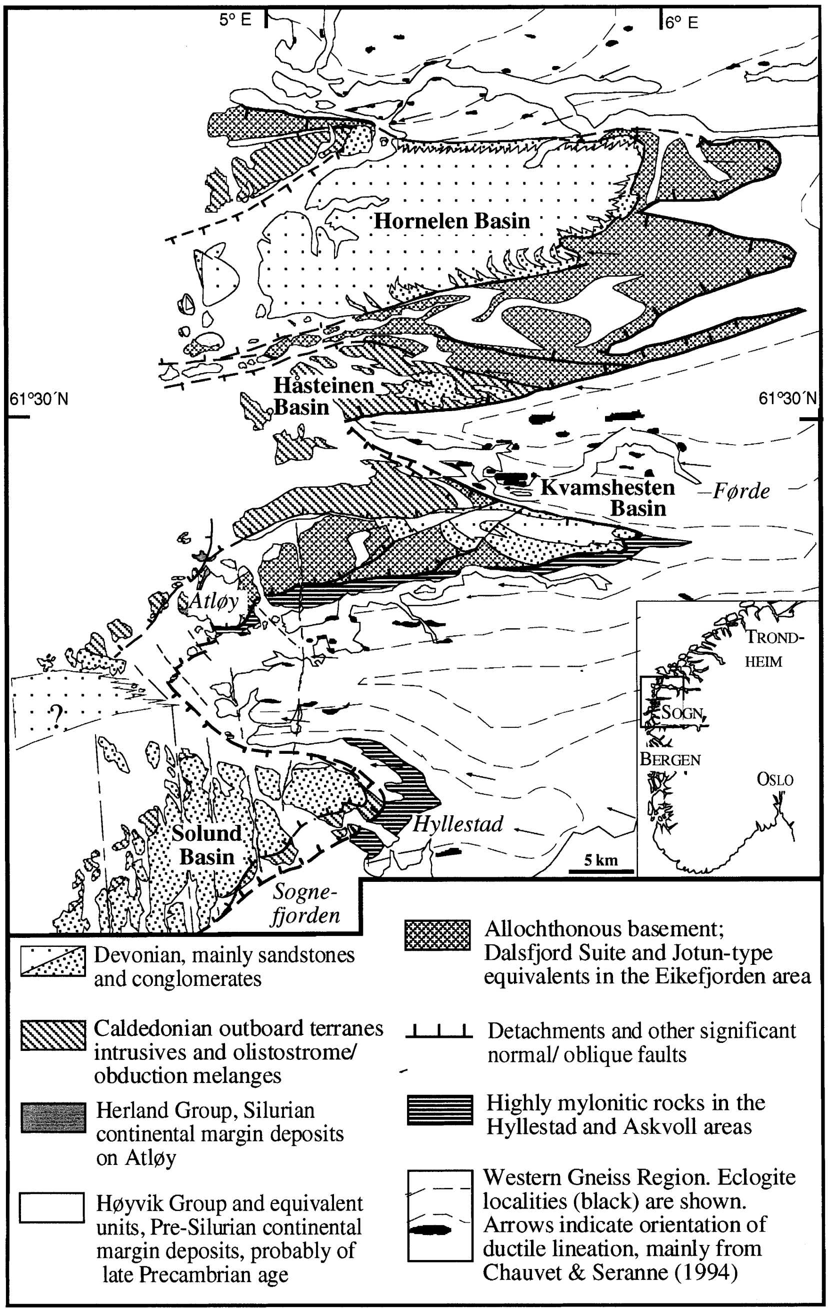

Fig. 1. Simplified overview map of the Sogn–Nordfjord area showing tectonostratigraphic units, main structural architecture and Devonian basins.

1 The geometry and distribution of individual sedimentary units and the geometrical relations between sedimentary units and depositional basement.

2 Relations between the basin fill and the Dalsfjord fault. The question whether the present basin margins were the original ones is highlighted by the documentation of young slip events along the basin boundaries.

3 The geometry and timing of intrabasinal faults with respect to sedimentation, the strain fields that can be inferred from them and their relations to the strain field encountered in the detachment zone. Significant syn-sedimentary intrabasinal faults have been suggested not to exist in the Devonian basins of western Norway (Seranne *et al.*, 1989). We dispute this interpretation.

4 Constraints on the syndepositional geometry of the original basin-bounding fault and on the mylonitic detachment zone. A principal discussion with respect to detachments is related to whether they are active at low dips, or if detachments initiate with a high dip (45° or more) and rotate towards a subhorizontal position (Jackson, 1987; Buck, 1988).

5 The geometry and timing of extension-parallel folds and thrusts. Extension-parallel folds have been described also in other areas that have undergone large-magnitude extension (Manktelow & Pavlis, 1994; Fletcher & Bartley, 1994).

6 The regional tectonic control on Devonian basin formation in Western Norway.

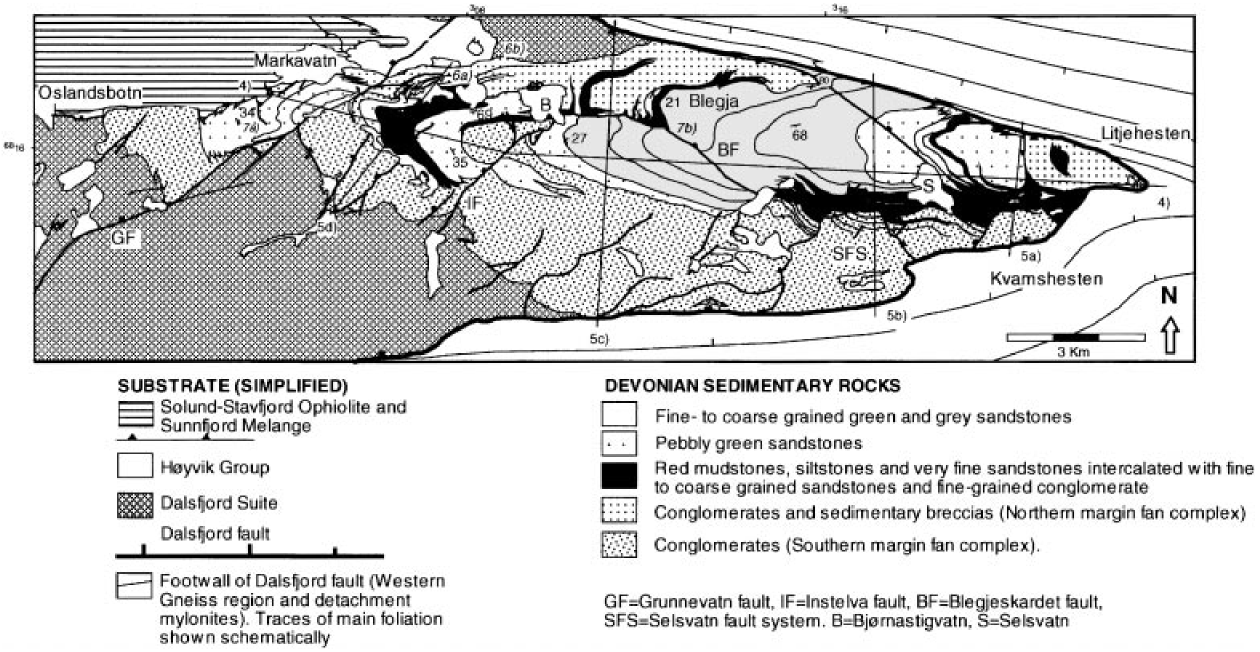

Fig. 2. Geological map of the Kvamshesten Basin showing distribution of main sedimentary units, as well as extensional and contractional intrabasinal structures. Map and profile figures to appear later in this paper follow legend outlined here. Note positions of sections in Figs 4 and 5. Letters in italics refer to logs in Figs 6 and 7.

Fig. 3. Eastern parts of the Kvamshesten Basin viewed from the north. The Dalsjord fault is outlined by the lowermost snow-covered area. Bedding dips towards the east, in a topographic section that is approximately east–west.

THE KVAMSHESTEN BASIN: BASIN FILL ARCHITECTURE – FACIES DISTRIBUTION AND RELATIONSHIPS

Four main lithological associations have been mapped in the Kvamshesten Basin. These are (1) conglomerates, (2) heterolithic units with abundant red, very fine-grained sandstone and siltstone, (3) green pebbly sandstones and (4) green fine- to coarse-grained sandstones. Each sedimentary unit contains vertical and lateral variations and display various relationships of interfingering and intergradation.

1. Conglomerates

The conglomerates along the southern and northern margins show distinct differences regarding internal organization, relationships to surrounding facies units and timing of initial deposition. Although the fanglomerates partly intercalate beneath the central parts of the

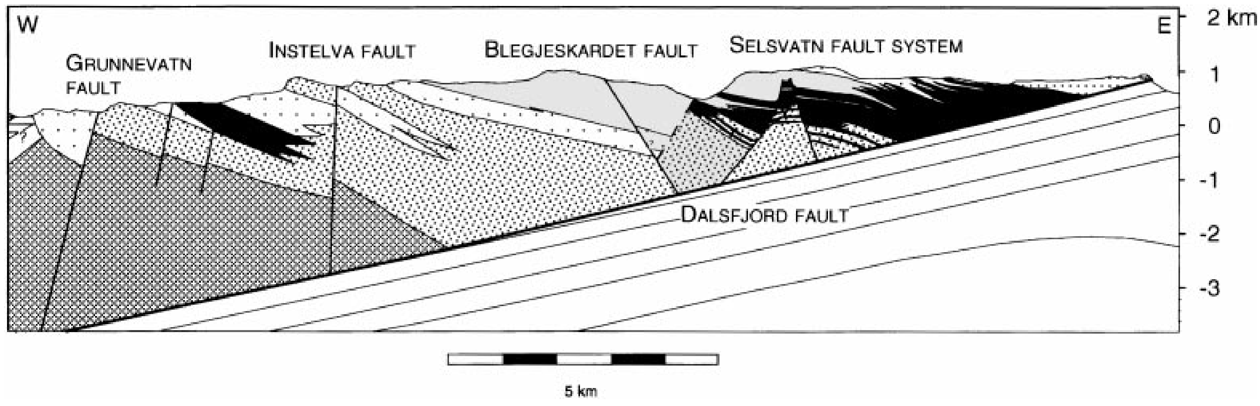

Fig. 4. East–west section through the Kvamshesten Basin. The profile is constructed parallel to the axis of the basinal syncline. Note break in slope of the basal unconformity across the Instelva fault, as well as the onlap relations towards basement as well as between sedimentary units. Note anticlinal geometry and fanning wedge geometry displayed by the Devonian strata in the eastern parts of the basin.

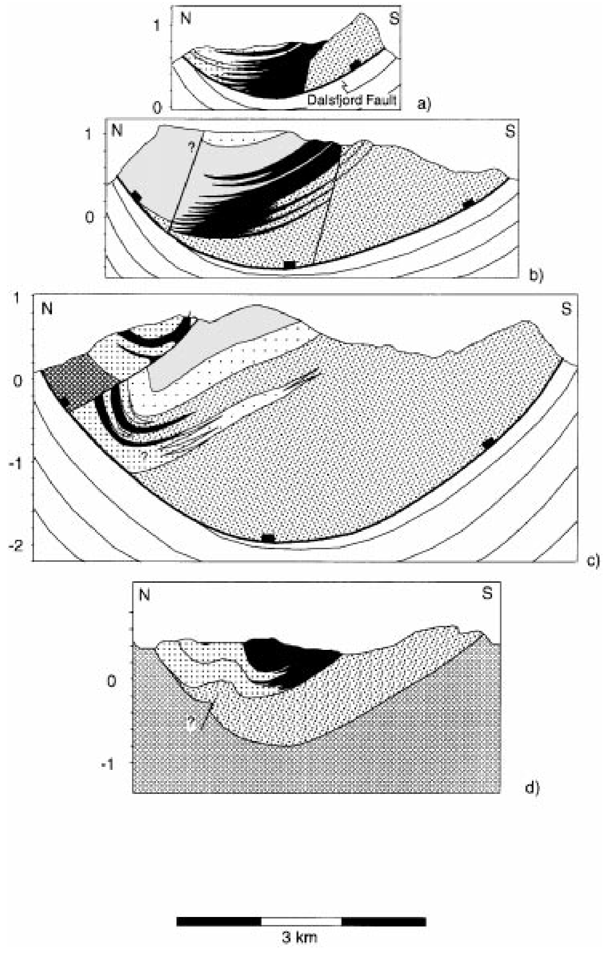

Fig. 5. North–south profiles through the Kvamshesten Basin. The profiles are constructed normal to the axis of the basinal syncline. Geometries of individual facies units at depth are schematic and variably speculative. Note that in (a), the southern margin fan complex is faulted out of the section. In (c), displacement on the Kringlefjellet reverse fault is dependent on the correlation of units in the map plane. The gradual widening of the preserved basin in (a–c) is due to the westerly plunge of the scoop-shaped Dalsfjord Fault. Correspondingly, the width of the preserved basin decreases in (d), due to the eastwards plunge of the basinal syncline.

basin, we find it convenient to describe the southern and northern margin units separately.

The southern margin fan complex

The wedge-shaped southern margin fan complex is exposed for more than 20 km, and is segmented into a series of NW-tapering fan bodies. Fan segmentation is mostly observed at medium to high stratigraphic levels. The fan complex reaches a present thickness of ≈2 km above the basement hangingwall cutoff, but thins dramatically in the area between the Instelva and Grunnevatn faults. In the hangingwall of the Grunnevatn fault, the fan complex thickens again to more than 1 km. Minor fans prograde into the hangingwalls of both the Instelva and Grunnevatn faults, to interfinger with sandstones that overlie the main fanglomerate body. Clast sizes are variable, but reach more than 2 m locally. With the exception of a number of outsized basement blocks interpreted as landslides (below), these are the coarsest deposits encountered in the basin. Clasts are generally subrounded, but subangular and well-rounded clasts are common. The clast population is dominated by syenitic gneisses, granites, gabbro, anorthosite and diorite, derived from the underlying Dalsfjord Suite (Skjerlie, 1971; Osmundsen, 1996). Sedimentary structures are generally scarce, but close to the top of the fan complex, trough cross-bedding and lenticular sandstone intercalations have been observed.

The northern margin fan complex

At low stratigraphic levels, the northern margin fan complex is segmented into a large number of fans. Close to the basin margin, individual fan segments constitute ≈100-m-thick coarsening upwards successions (Fig. 6a). Along west-central parts of the northern basin margin, fans onlap the depositional substrate. Above the hangingwall cutoff of basement, individual fan segments are rooted in a ≈1-km-thick, wedge-shaped fanglomerate body. The rock types that constitute the northern margin

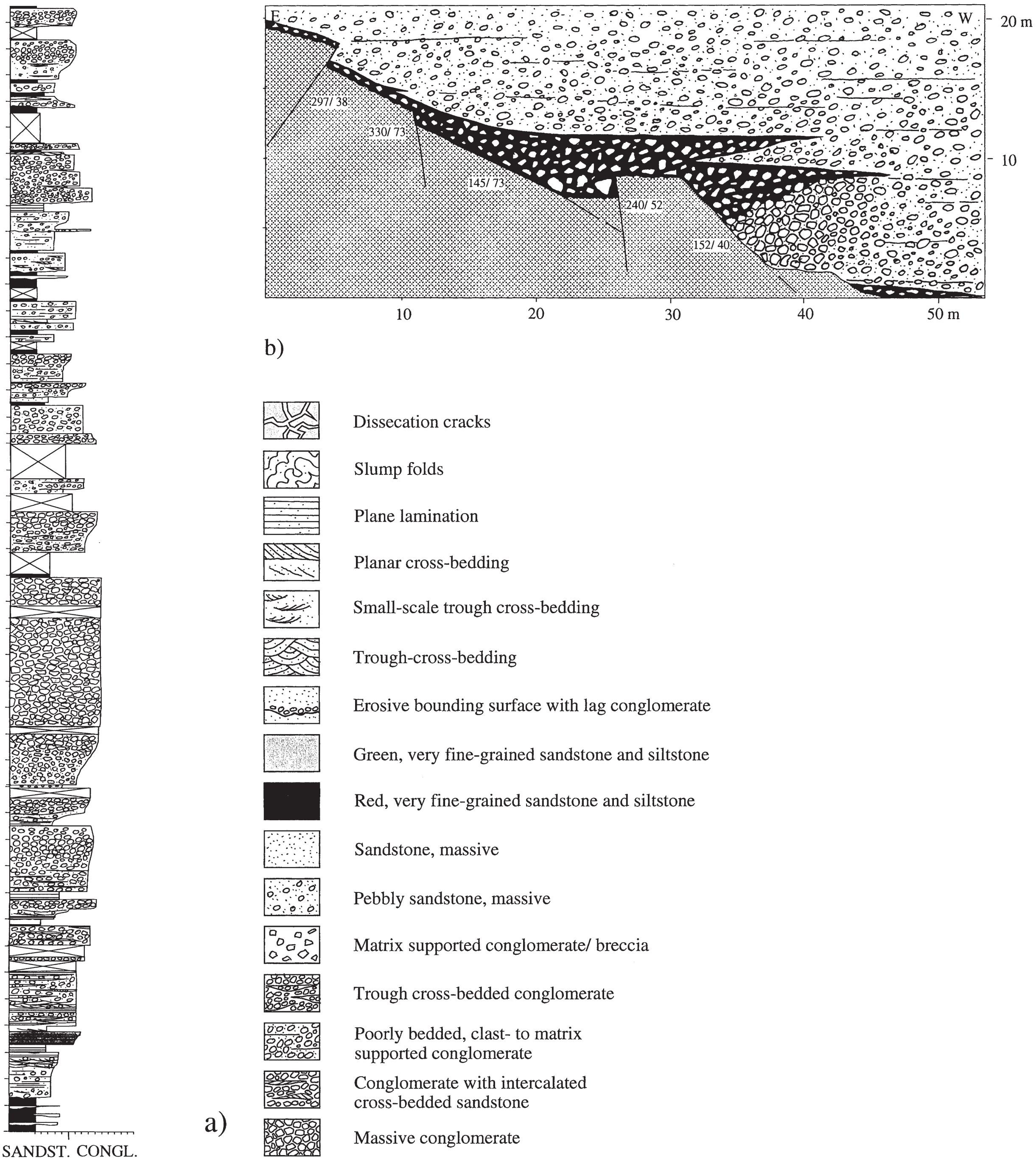

Fig. 6. Vertical scales are in metres for these and following logs. The grain-size scale of this and other logs follows the modified Wentworth scale of Lane *et al.* (1947), reproduced by the American Geological Institute. Vertical scales are in metres for this and logs in Fig. 7. Legend applies also to Fig. 7. (a) Log through some 200 m of the northern margin fan complex. Note organization in coarsening-upwards successions at various scales. Also, note variations in lithofacies in the coarse-grained units. (b) Lateral log of outcrop at northern basin margin. Small fans of sedimentary breccia with abundant red matrix intercalate with clast- to matrix-supported cobble and boulder conglomerates with green sandstone and fine gravel matrix. The sediments drape a palaeotopography that displays small, synsedimentary fault scarps. Clasts are generally of cobble size in the green conglomerates, while the angular blocks of the fans reach metre size.

fan complex can be described as (1) sedimentary breccias, (2) massive to crudely bedded conglomerates and (3) cross-bedded conglomerates with sandy interlayers.

1 The clast- to matrix-supported breccias commonly occur as thin (<5 m) sheet-like drapes on the basal unconformity, as infill in palaeotopographical lows and as lenticular and fan-shaped bodies that intercalate with conglomerates or sandstones (Fig. 6b). Eastwards along the northern basin margin, breccias intercalate with progressively higher stratigraphic levels of the basin fill (Bryhni & Skjerlie, 1975). In the north-central basin area, two comparably large fan segments have been classified

as sedimentary breccias (Osmundsen, 1996). Based on clast populations derived mainly from the local depositional substrate to the north and west of the basin, we infer that a number of small, fan-like bodies of sedimentary breccia along the basal unconformity prograded south or south-east into the basin. The breccias in the central basin area have provenance in the Dalsfjord Suite and probably had a westwards component of progradation (Osmundsen, 1996).

2 Massive and crudely bedded conglomerates comprise a volumetrically significant part of the northern margin fan complex (e.g. Fig. 6). The coarsest and thickest deposits of this type are found above the hangingwall cutoff of the basement, where clasts reach boulder size (up to 1 m).

From the massive conglomerate complex in the NE, smaller fans splay off to intercalate with the heterolithic units of the central basin area. Basinwards progradation is usually associated with grain size reduction and increased abundance of structures that indicate fluvial transport.

3 Cross-bedded conglomerates occur at several stratigraphic levels and often constitute the lower parts of large-scale, conglomeratic coarsening-upwards successions (Fig. 6a). Clasts are subrounded to rounded and generally of pebble to cobble size. Elongate cluster bedforms with imbricate clasts, wedge-shaped lenses of cross-bedded sandstone and sheet-like bodies of massive conglomerate are common in the cross-bedded conglomerates. Towards the NE, the cross-bedded conglomerates grade laterally into the more proximal massive and crudely bedded conglomerates. Towards the central basin area, the cross-bedded conglomerates grade laterally into sandstone.

2. Heterolithics with abundant red very fine-grained sandstone and siltstone

Generally, the rock units mapped as heterolithic units contain more than 30% of red, very fine- to fine-grained sandstone and siltstone that intercalate with green sandstones or conglomerates. Red fines occur also in surrounding rock units, but in significantly lower proportions. Red fines are particularly common within three areas of the Kvamshesten Basin, notably in the west-central parts, along the central part of the northern basin margin and along the south-eastern basin margin. Within the red, fine-grained sandstones, sedimentary structures are common and dominated by plane and climbing ripple lamination.

3. Green pebbly sandstones

The pebbly sandstones typically occur in cycles of varying thickness, separated by red, fine-grained beds (Fig. 7a). Sedimentary structures are dominated by trough cross-bedding, planar cross-bedding and plane lamination, out of which the two former dominate. Pebbles drape through-shaped erosive boundary surfaces or are dispersed in the sandy matrix. At low to medium stratigraphic levels, the amount of intercalated, red fine-grained deposits increases upwards, and the pebbly sandstones merge laterally as well as vertically into the heterolithic units described above.

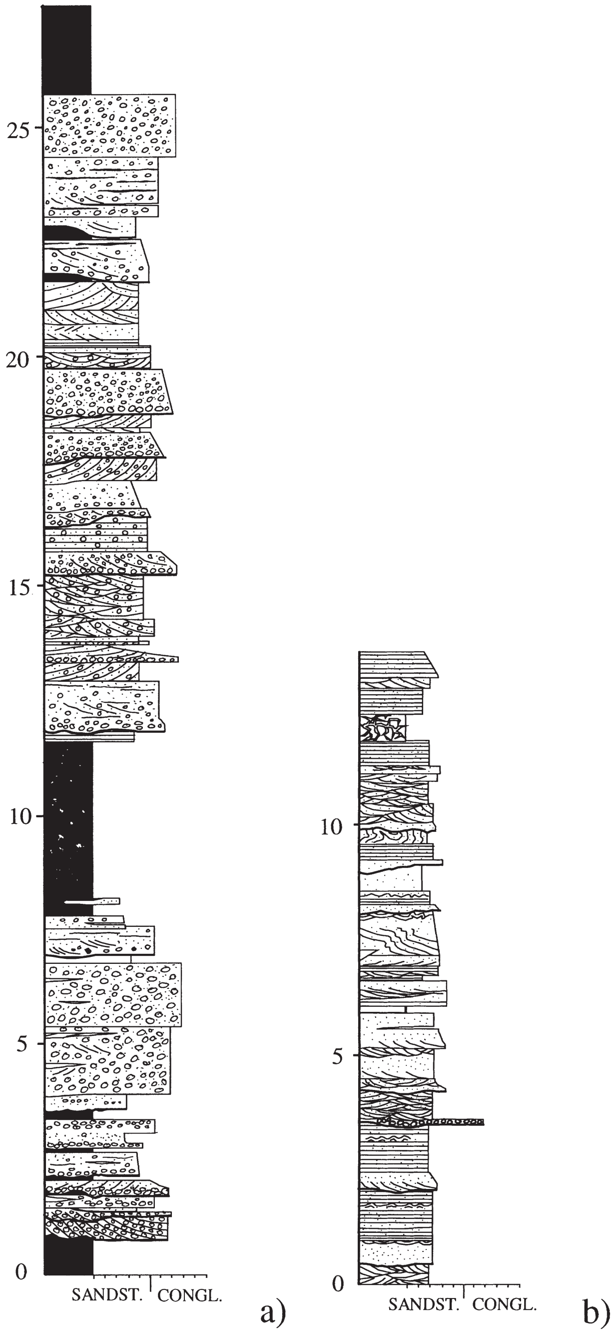

Fig. 7. Logs from two stratigraphic levels in the sandstones of the central basin area. (a) Trough cross-bedded, pebbly sandstones intercalated with red fines. From area west of the Gunnevatn fault. (b) Plane laminated and trough cross-bedded, medium-grained sandstones, south of Blegja. The subdivision of the sandstones is mainly based on the overall reduction in grain size, and on the increased abundance of plane lamination that characterizes the fine- to medium-grained units.

4. Fine- to coarse-grained green and grey sandstones

The sandstones that crop out in the east-central part of the basin are fine to coarse grained, less pebbly and commonly display trough and planar cross-bedding (Fig. 7b). Plane laminated sets constitute a larger proportion of the stratigraphic column than in the pebbly sandstones. Red very fine-grained sandstones and siltstones are rare through much of the green sandstones, but reappear at high stratigraphic levels where the green sandstones interfinger with heterolitic units. Intercalations of green siltstone and very fine-grained sandstone are, however, common. Pebbles recur in the sandstones along the north-eastern basin margin in a position proximal to the conglomerates in the easternmost basin area.

Landslides

Several large (tens to hundreds of metres) blocks of metamorphosed igneous and sedimentary rocks crop out at low, medium and high stratigraphic levels in the Kvamshesten Basin (Fig. 2), including the highest stratigraphic level exposed in the basin at Litjehesten. Block lithology seems to reflect closely lithological units found in the depositional substrate, notably rocks of the Sunnfjord Melange, Høyvik Group and Dalsfjord Suite (Markussen, 1994; Osmundsen, 1996). The basement blocks are variably brecciated, but apparently not faulted against their substrate of Devonian sedimentary rocks. Clastic dikes are found locally, and where the Devonian strata below the blocks can be studied in detail, small-scale normal faults and slump folds are present (Markussen, 1994). Based on the above observations, we interpret the basement blocks to represent landslides similar to the ones described by Bryhni (1975) from the Solund Basin.

General facies interpretation

The clast-supported *conglomerates* of the southern margin fan complex were probably deposited by stream-related processes. The large clast sizes and the general lack of well-defined sedimentary structures at low stratigraphic levels indicate that the conglomerates were deposited on the proximal parts of an alluvial fan, characterized by fairly steep topographic gradients and high-energy streamflow conditions (see also Steel *et al*., 1985). In their interpretation the conglomerates along the northern basin margin were deposited on small, debris-flow-dominated fans. We agree that the sedimentary breccias along the northern basin margin were probably deposited by massflow type processes and in the central basin area, angular clasts chaotically orientated in a red fine-grained matrix suggests a debris-flow origin for some of the fanglomerates (Osmundsen, 1996). The cross-bedded conglomerates are, however, clearly fluvial in origin; this is probably also the case with some of the crudely bedded conglomerates. Thus, in our interpretation, fluvial deposits were more important in the northern margin fan complex than indicated previously. Also, our map of the northern basin margin differs from that of Steel *et al.* (1985), as individual fan segments are rooted in a kilometre-thick, wedge-shaped complex above the basement cutoff. In the interpretation of Steel *et al.* (1985), palaeocurrent directions along the basin margins were towards the central basin area, that is towards the south and SW in the conglomerates of the northern basin margin, and towards the north and NW along the southern basin margin.

The *sandstones* of the central basin area are undoubtely fluvial in origin, and record lateral and vertical variations in fluvial style. Based on the abundance of plane and ripple laminated, red very fine-grained sandstone and siltstone, the heterolithic units are interpreted to represent floodplain/floodbasin deposits. The distribution of the heterolithic units through the basin stratigraphy indicates that the locus of the floodplain shifted several times during deposition. The green, pebbly sandstones are interpreted as channel and bar deposits. Based on the predominance of relatively coarse-grained pebbly sandstones over red fines through much of the section, we interpret the pebbly sandstone units to represent a braided fluvial environment. The existence and lateral persistence of red, fine-grained sandstone and siltstone beds within the pebbly sandstones indicate that flooding was occasionally widespread, and point towards a system of some sinuosity. Asphaug (1975) reported palaeocurrent directions that were towards the east in the sandstones of the central basin area. The fine- to coarse-grained green sandstones exposed in the east-central parts of the basin contain a higher percentage of plane lamination, and may represent a more ephemeral fluvial system. Most likely, the green, fine- to coarse-grained sandstones were deposited on a sandy fluvial plain, in a position more distal with respect to the source area than the pebbly sandstones. The sandy fluvial plain was associated with a floodplain located along the present SE basin margin. In the SE, the floodplain received coarse debris from the southern margin fan complex.

The organization of the northern margin fan complex into upwards-coarsening units at a variety of scales (Fig. 6) differs from the less well organized, massive conglomerates encountered at low stratigraphic levels in the southern margin fan complex. The coarsening-upwards motif recognized in the fanglomerates of the northern margin can be traced into the sandstones of the central basin area, as documented earlier from the Hornelen Basin (e.g. Steel & Gloppen, 1980). A log through some 200 m of the westernmost parts of the southern margin fan complex (Osmundsen, 1996) revealed, however, that the organization of conglomerates at low stratigraphic levels along the southern margin is less distinct, or occurs at a different scale than on the northern margin. At high stratigraphic levels, the

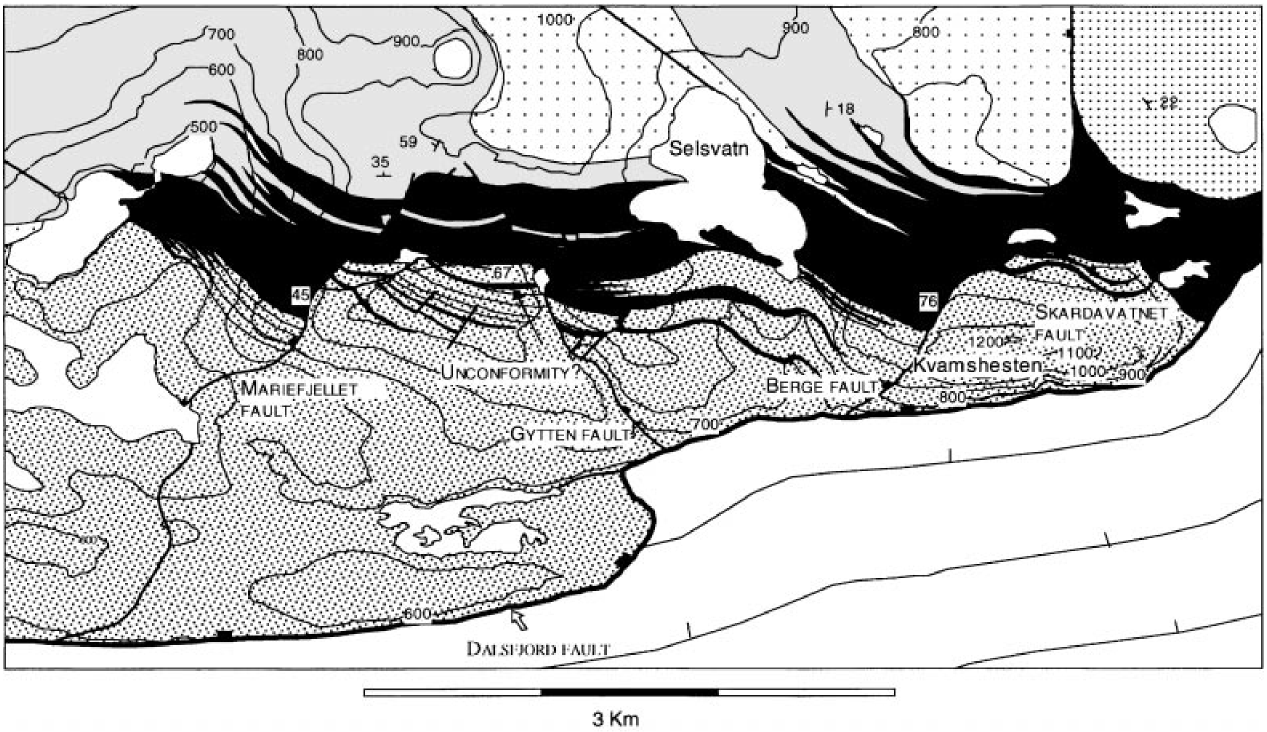

Fig. 8. Detailed geological map showing main facies units and synsedimentary faults in the Selsvatn area. Note that in the hangingwalls of the Mariefjellet and Berge faults, the intercalated contact between grey and green sandstones (dense stipple) and heterolithics (black) migrates stratigraphically upwards towards the faults, indicating synsedimentary activity. The Selsvatn fault system is rotated on the flank of the basinal synform, but constitutes an orthorhombic fault system when restored with bedding. See discussion in text. Note angular dislocation in the footwall of the Gytten fault.

organization of the southern margin fan complex is similar to low stratigraphic levels of the northern margin fan complex. A very rough fining-upwards motif may be defined on the basin scale, and is related to the eastwards migration of the basin depocentre. The eastwards depocentre migration is also shown by the geometry of the sandy facies units (Fig. 4). The rough fining-upwards motif was apparently interrupted by distinct episodes of fan progradation far into the basin, notably at medium and high stratigraphic levels. Thus, the Kvamshesten Basin apparently contains a cyclicity at a scale of several hundred metres, repeated 3–4 times through the basin stratigraphy.

The importance of the *landslides* described briefly above is related to their provenance in the Caledonian nappe units. During deposition of the entire preserved stratigraphy, the topography that surrounded the Kvamshesten Basin must have been developed in the hangingwall of the detachment zone. Also, the syndepositional topography must have been significant enough for large rock masses to be emplaced into the basin by gravity-driven, probably tectonically triggered processes.

Marginal and intrabasinal unconformities

In the Hornelen and Kvamshesten basins, a number of intrabasinal unconformities were proposed by Seranne *et al.* (1989) and by Chauvet & Seranne (1994). Some of the proposed unconformities have been rejected in the Hornelen (Wilks & Cuthbert, 1994) and Kvamshesten (Osmundsen, 1996) basins. East of the Instelva fault, progressive westward onlap onto depositional basement is evidenced by the wedge-shape of the marginal conglomerate complexes. The exact geometry of this onlap is difficult to quantify due to the general lack of bedding at low stratigraphic levels. Along the NW basin margin, the Devonian strata display a low-angle onlap onto basement (Bryhni & Skjerlie, 1975; Seranne *et al.*, 1989) although, locally, the basement is faulted against the Devonian (Fig. 9). The unconformity, where preserved, generally displays an E–W orientation. At low stratigraphic levels west of Markavatn (Fig. 2) the direction of onlap is mainly towards the north and north-east, as NE-dipping pebbly sandstones are separated from the unconformity only by a thin zone of sedimentary breccia or conglomerate. In the area north of Bjørnastigvatn, onlap is more easterly (Fig. 10). Small-scale, fault-related palaeotopography is present along the contact and makes its orientation somewhat variable (Fig. 6). North of Blegja, an intrabasinal unconformity displays downwards truncation of strata to the west. Inside the basin, a number of discontinuities occur that lack critical exposure. West of the Gytten fault, beds are apparently truncated stratigraphically downwards towards the west (Fig. 8). An apparent truncation of beds downwards towards the east has been observed in the Litjehesten

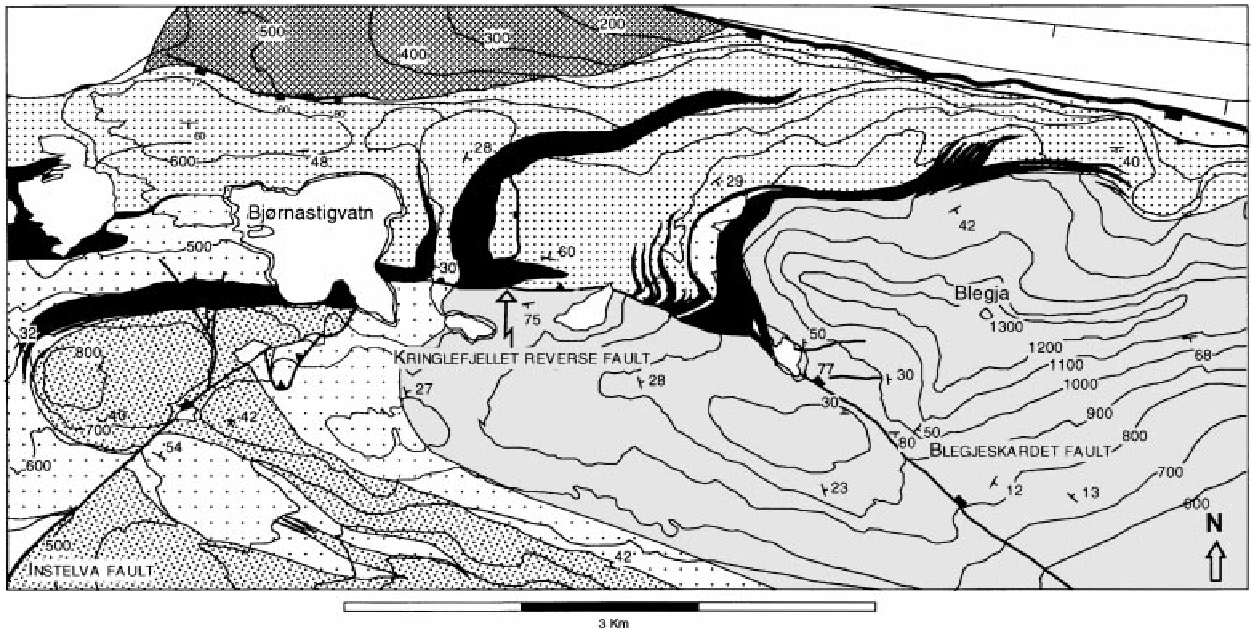

Fig. 9. Detail map of parts of the central basin area. The map shows the distribution of sedimentary units in the area, as well as the relations between the Kringlefjellet reverse fault and the Instelva and Blegjeskardet faults.

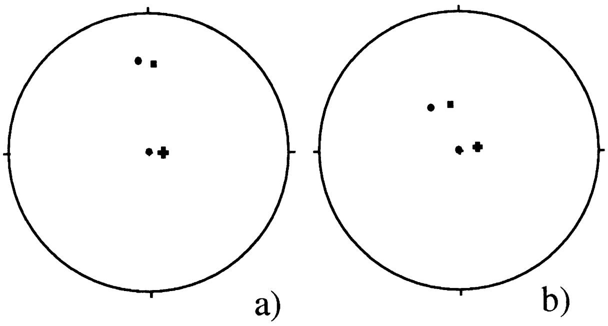

Fig. 10. (a) Stereographic (Schmidt-net) representation of basal unconformity (square) and bedding (cross) north of Bjørnastigvatn. When bedding is rotated to a horizontal position, the unconformity (filled square) displays a westwards dip. This shows that the onlap relationship along this part of the northern margin cannot be related to a southerly dipping fold flank, as indicated by Chauvet & Seranne (1994). See text for discussion and further inferences. $n = 4$. (b) Intrabasinal unconformity north of Blegja. If bedding above the unconformity (cross) is rotated to a horizontal position, the beds below the unconformity dip towards the west-southwest (circle unrotated, square rotated position of bedding below unconformity). $n = 4$.

area. In the central basin area (Fig. 9), a discontinuity occurs in the northern margin fan complex between the conglomerates that rest directly upon the basal unconformity and the overlying succession of fanglomerates and red fines. The discontinuity cuts stratigraphically downwards in a northwards direction. The plane of discontinuity apparently marks the base of a stratigraphic level characterized by increased basinwards fan progradation. An interpretation of this as an internal unconformity is, however, somewhat ambiguous, as it occurs in an area of transfer and accommodation of compressional strains (Osmundsen, 1996).

STRUCTURAL GEOLOGY

Normal and oblique faults

Along the southern basin margin, the Devonian unconformity is cut by an array of NW-dipping, steep faults that terminate stratigraphically upwards in the southern margin fan complex, or near the conglomerate–sandstone interface (Fig. 11a). Some of the faults can be traced towards the detachment zone where they are cut by the Dalsfjord fault. The Grunnevatn fault (Skjerlie, 1971; Fig. 2) apparently accommodates a map-plane displacement of more than 2 km on the southern basin margin, but produces only negligible displacement where it cuts the northern basin margin (Fig. 2). Across the Instelva fault, the thickness of the lower part of the southern margin fan complex is reduced by ≈1 km. To the east of the Grunnevatn fault, a NE-dipping fault displaces the unconformity by more than 200 m down to the north-east.

East of the hangingwall cutoff of the basement, the Selsvatn fault system (Fig. 8) comprises an array of NW- and NE-dipping faults that cut the boundary between the southern margin fan complex and the floodplain/floodbasin sequence (Figs 11 and 13b). Displacements at this stratigraphic level are of the order of 150–500 m. Stratigraphically upwards, displacement decreases rapidly and the faults pass into monoclinal flexures. For a distance of ≈1.5 km, bedding in the hangingwalls of the Mariefjellet and Berge faults displays a more northerly strike than the subregional E–W strike encountered in

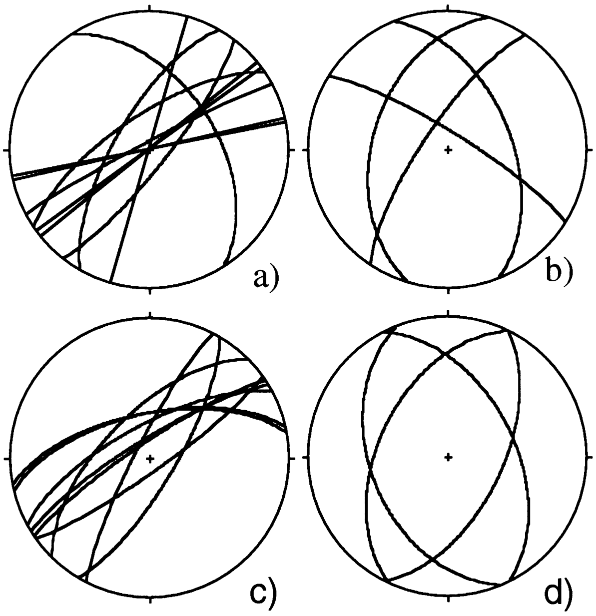

Fig. 11. Stereographic (Schmidt-net) representations of synsedimentary intrabasinal faults in the study area. (a) Present orientations of oblique faults that cut the basal unconformity. $n = 10$. (b) Present orientation of main faults of the Selsvatn fault system. (c) Faults in (a) unfolded and back-roatated with bedding. $n = 10$. (d) Data in (b) unfolded and back-rotated. The synsedimentary orientations of the four main faults reveal that the Selsvatn fault system originated as an orthorhombic fault system characterized by positive elongation in east–west and north–south directions. See discussion in text.

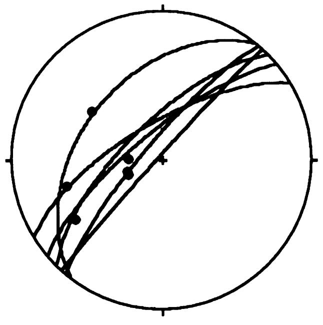

Fig. 12. Stereographic (Schmidt-net) representation of striated fault planes and shear fractures along the southern basin margin. The relative age of fault movement could not be demonstrated for any of the faults represented here and it is uncertain whether the striae record movements that are syn- or post-sedimentary. Within the present configuration of the fault planes, the lineations record displacements that are between normal and sinistral. $n = 12$.

the footwalls. Towards the west, the regional E–W strike of bedding is gradually restored. Although the regional E-trending fold pattern could produce deflections of this type, the close association with the faults suggest that the deflections were genetically related to the faults. Adjacent to the fault planes, a low-wavelength, oblique drag of bedding is observed. To the north-west of the Mariefjell and Berge faults, the lower boundary of the green, fluvial sandstones shows a considerable stratigraphic climb without migrating much further (south) eastwards into the basin. Between the faults, the lower green sandstone boundary occupies a fairly constant stratigraphic level (Fig. 9). Some of the larger faults contain excess stratigraphy in their hangingwalls (Fig. 8). Lineations have been recorded from a restricted number of faults along the southern basin margin (Fig. 12). In general, lineations are oblique and indicate relative west to south-west displacement of the hangingwalls (present configuration).

Contractional structures

Contractional structures encountered within the Kvamshesten Basin comprise folds, reverse faults and fault-propagation folds. Generally, the contractional structures display east and south-east trends.

Folds

The Kvamshesten Basin and its depositional substrate is deflected by a large-scale, gently E-plunging syncline (Skjerlie, 1971), and by a number of parasitic folds on a variety of scales. The main syncline is open with an upright to steeply N-dipping axial plane. Trend of the fold axis as calculated from readings of bedding is 090° ± 5° through most of the basin (Fig. 13). West of the Instelva fault, however, the trend is 100–105°. The plunge of the fold axis decreases systematically through the basin, from values close to 30° at low stratigraphic levels to 8–9° in the uppermost parts of the stratigraphy. A closed anticline (Fig. 5) with a steeply N-dipping axial surface and an amplitude of several hundred metres can be traced through large parts of the basin. The steep southern limb of the anticline is cut by the Kringlefjellet reverse fault (see below). Open to closed folds with amplitudes one order of magnitude less than the main syncline are present through most of the basin fill (Fig. 14a). In the heterogeneous sequences rich in red siltstone and sandstone, folds with amplitudes of a few metres are frequently found. The thicker (i.e. > 10 m) gravel beds are generally not deflected by folds of this magnitude. Thus, dislocations exist between beds deflected by folds of different wavelength and amplitude. N- to NE-plunging lineations recorded from fine-grained bedding surfaces in the south-central basin area were interpreted as flexural slip lineations by Markussen (1994).

Reverse faults

Along segments of both the northern and the south-western basin margins, the Devonian basin fill is overthrusted by rocks of the local depositional substrate (Fig. 2). Two reverse faults that cut the northern basin margin die out upsection in the Devonian rocks, and give way to E-plunging fault-propagation folds. Displacement on one of these faults is of the order of some tens of metres. For other thrusts (Fig. 14b),

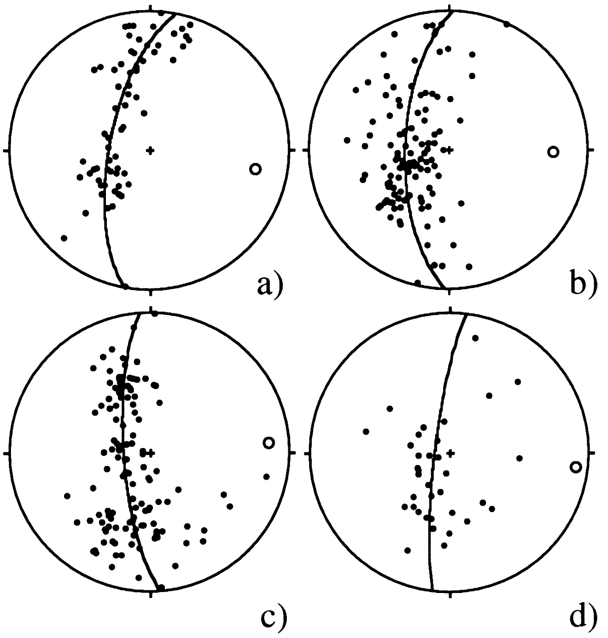

Fig. 13. Stereographic (Schmidt-net) representation of bedding from low to high stratigraphic levels in the Kvamshesten Basin. The basin has been divided into four domains that correspond to progressively higher stratigraphic levels in the basin. Poles to best fit great circles have been calculated for each stratigraphic level, to record any changes in plunge for the basin syncline. A general decrease in plunge is observed from low to high stratigraphic levels. The decrease in plunge is interpreted to represent an original fanning wedge relationship in the Devonian strata. (a) Central basin area between the Grunnevatn and Instelva faults. Pole to best-fit great circle 101/23. $n = 70$. (b) Bjørnastigvatn–Blegja area. Pole to best-fit great circle 092/26. $n = 121$. (c) Kvamshesten–Blegja area. Pole to best-fit great circle 086/15. $n = 127$. (d) Litjehesten area. Pole to best-fit great circle 097/08. $n = 35$.

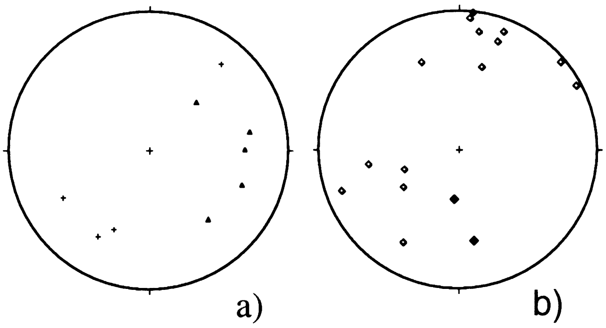

Fig. 14. Stereograms of outcrop-scale structural elements related to north–south shortening of the Kvamshesten Basin. (a) Fold axes (triangles) and axial planes (crosses) of outcrop-scale folds, central basin area. $n = 9$. (b) Small-scale reverse faults (open diamonds) and Kringlefjellet reverse fault (closed diamonds). The scatter in orientation displayed by the small-scale structures indicate that early contractional structures were rotated prior to formation of the Kringlefjellet fault. $n = 16$.

displacements are generally unconstrained as the basal unconformity is not preserved in the hangingwalls. In the central basin area, the E–W-striking Kringlefjellet reverse fault (Fig. 9) cuts the anticline described previously. In our interpretation (Fig. 5c), the reverse fault juxtaposes basement with Devonian at depth. Stratigraphic separation may approach 1 km. The Kringlefjellet reverse fault merges with the Instelva and Blegjeskardet faults, respectively. In the hangingwalls of these faults, the basin fill is deflected by fold trains that are not recognized in the trapezoid-shaped fault block that constitutes the footwall. At the scale of outcrop, many small-scale reverse faults have been observed. These range from apparently ductile structures with no sign of cataclasis or brittle fracture (Fig. 15) to entirely brittle faults marked by discrete fractures. Locally, reverse faults that cut heterolithic rock units display apparently ductile smears of red, fine-grained siltstone along the fault planes. A number of folds and reverse faults (Fig. 14) display orientations that deviate significantly from the E–W trend defined by the Kringlefjellet reverse fault and by the basinal syncline.

TECTONOSEDIMENTARY RELATIONSHIPS

The Dalsfjord fault

In E–W section, the Dalsfjord fault cuts down to the west through the basin and its depositional substrate. In N–S section (Figs 5 and 16), it is evident that the fault cuts the large-scale, E–W-trending folds in the basin as well as major lithological units like the southern margin fan complex. The scoop-shaped Dalsfjord fault has a more gentle amplitude than the folds in the basin fill (see also Torsvik *et al.*, 1986). As no clasts from the Western Gneiss Region nor from the extensional mylonite zone have been identified in the basin fill, the juxtaposition of Devonian sediments with extensional mylonites across the Dalsfjord fault cannot have taken place at the surface at the time of deposition. The Permian and Mesozoic resetting of magnetic fabrics in the fault zone (Torsvik *et al.*, 1992) confirms that the Dalsfjord fault accommodated post-Devonian displacement. The Dalsfjord fault apparently also excises part of the detachment mylonites in its footwall (maps and profiles by Kildal, 1970; Hveding, 1992). The above observations demonstrate that the Dalsfjord fault does not represent the Middle Devonian basin margin. More likely, the basin was rotated out of its original position during N–S shortening and later cut by the fault.

Constraints on syndepositional basin-margin morphology

The fault that controlled sedimentation in the Kvamshesten Basin is nowhere preserved. The apparent lack of rocks from the Western Gneiss Region and the detachment mylonites in the conglomerates as well as lithologies exposed in landslides found at high stratigraphic levels indicate that the basin-bounding fault must

Fig. 15. Small-scale, soft-sedimentary reverse fault, Leknesvatna. The fault is rooted in planar cross-beds (lower part of photograph). The fault plane can be traced as a localized, but apparently ductile zone of deformation through the coarse-grained layer in the upper half of the photograph.

Fig. 16. The Dalsfjord fault viewed from the east along the south-eastern basin margin, towards Kvamshesten mountain. The fault is outlined by the marked break in topography and vegetation, and clearly truncates the steeply dipping beds along the basin's south-eastern margin.

have been developed entirely in the hangingwall of the detachment zone. As the Dalsfjord fault cross-cuts the synsedimentary configuration, the dip of the synsedimentary basin-bounding fault cannot be exactly quantified. Independent evidence is provided, however, from the size and geometry of the marginal deposits. The size of the southern margin fan complex indicates that the basin-bounding fault on the south-east margin had a moderate or shallow north-westwards dip, as fan size is usually taken to be directly proportional to the size of the drainage basin that feeds the fan (Leeder & Gawthorpe, 1987). Drainage basins that develop in the footwalls of steep normal faults are not extensive enough to provide large amounts of sediment. The exposed footwall of a low-angle fault will constitute a much larger drainage area than the footwall of a steep normal fault. Thus, the low-angle normal fault will have the potential of producing a larger alluvial fan (Friedman & Burbank, 1995). The large clast sizes encountered in the marginal fan complexes suggest, however, that significant topography existed in the feeder drainage basin. Another line of argument based on clast provenance studies was presented for the Hornelen Basin by Cuthbert (1991). No eclogite clasts were identified in the Hornelen Basin, and the metamorphic grade of the clast population was not found to increase upwards through basin stratigraphy. Thus, Cuthbert (1991) concluded that the 50 km of displacement inferred for the syndepositional Hornelen Basin bounding fault must largely have taken place along a low-angle fault. We have found no clasts of eclogite in the Kvamshesten Basin, and a similar argument applies here, strongly supported by the geometrical and tectono-sedimentary relationships referred above. The presence of a large-scale rollover anticline–syncline pair during basin deposition indicates that the basin-bounding fault had a ramp-flat topography at depth. The detachment zone was probably at depth during the formation of the basin. Based on Ar–Ar geochronology (Chauvet *et al.*, 1992) and on *P–T–t* modelling, Wilks & Cuthbert (1994) concluded that the rocks of the Western Gneiss Region in the Hornelen Basin area were at a depth corresponding to 300 °C at the time of basin deposition. We suggest that in the Kvamshesten Basin area, the basin-controlling fault detached along the mylonite zone. Although the cutoff angle between the Devonian unconformity and the top of the extensional mylonites is ≈45°, the restoration of the unconformity to shallower dips away from the fault suggests a rollover shape that is most consistent with a ramp-flat normal fault that soles into a basal detachment at depth.

Geometry and age relationships of facies units

From our map (Fig. 2) it is evident that the southern margin fan complex contains stratigraphy that cannot be recognized in the north. West of Markavatn, the unconformity is onlapped by sandstones that are stratigraphically higher than the southern margin fan complex. Several hundred metres of stratigraphy must have been deposited in the southern margin fan complex prior to the onset of sedimentation on the northern basin margin. Thus, the oldest sediments in the Kvamshesten Basin are encountered along the present southern basin margin, on the present north-east flank of the basinal synform.

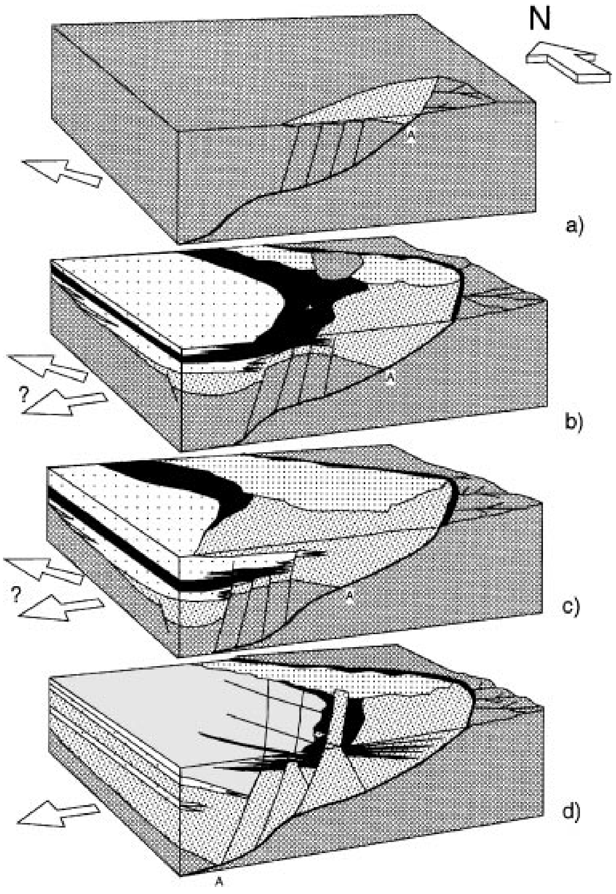

Fig. 17. Schematic 3D cartoon for the tectonosedimentary development of the Kvamshesten Basin. (a) A NW-dipping normal fault controlled deposition of the lower part of the southern margin fan complex (see text). The present northern basin margin was an area of nondeposition or erosion at this stage. The basal deposits onlap basement towards the north-west, north and north-east in the preserved basin area. Probably, a SW-dipping transfer fault developed along the northern basin margin towards the end of this stage. Also, an extensional rollover was developing. The basin was extending in a north-west direction. Evidence for this stage is mainly the onlap and time-relations observed at low stratigraphic levels in the westernmost basin area. (b) Tectonosedimentary framework during deposition of lower middle (preserved) stratigraphic levels. At this time, the depositional systems corresponding to the northern margin fan complex and the sandstones of the central basin area were established. The basin was bounded by faults in the south-east and north, and coarse debris was transported basinwards from the margins. While fluvial processes dominated in the south, the northern margin was characterized by both fluvial and debris flow processes, probably controlled by a fault with a steeper dip than the one at the south-eastern margin. In the central basin area, a sandy fluvial environment persisted, fining gradually upwards from the pebbly braided channels represented by the pebbly green sandstones to the floodplain represented by the heterolithic units. The heterolithic unit is fairly symmetrically distributed in the (preserved) basin. Palaeocurrents were flowing east–west, at least periodically towards the east. This indicates that some of the sandstones were sourced in the hangingwall of the basin-bounding fault. The sediments onlapped the crest of an evolving rollover anticline from the (south)east and (north)west, respectively, producing thickness variations in the marginal fan complexes. Evidence for this stage is the distribution of sedimentary units mapped by us, the onlap relations onto basement at medium stratigraphic levels (Bjørnastigvatn area), onlap relations onto the top of the southern margin fan complex and synsedimentary activity on NE-striking intrabasinal faults. (c) At middle stratigraphic levels, an episode of marked fan progradation took place from both the northern and the southern basin margins. A fan segment several hundred metres thick prograded from the southern basin margin towards the central basin areas. Correspondingly, a series of thick conglomeratic fans prograded basinwards from the northern margin and intercalated with floodplain deposits. Apparently, the floodplain shifted its position relative to stage (b), where it covered a larger part of the basin floor, to a more restricted area along the northern margin during this stage. Evidence for this stage is mainly the configuration of sedimentary units. (d) At high stratigraphic levels, the main locus of the floodplain had shifted southwards, and was receiving coarse debris from fan segments that prograded basinwards from the southern margin fan complex. The floodplain was interacting with the fluvial channel belt. The fluvial channel belt was migrating (south)eastwards together with the floodplain, as a response to progressive eastwards tilting of the basin. The eastwards migration of the fine-grained fluvial units was apparently hindered temporarily by subsidence on the intrabasinal faults in the Selsvatn fault system. The basin was extending in east–west and north–south directions. Evidence for this stage comprises the distribution of sedimentary units mapped by us and the strain field deduced from the orthorhombic Selsvatn fault system.

The onlap observed in the westernmost parts of the basin together with the overall geometry of the southern margin fan complex is consistent with a southwards component of tilt of the basin floor during early stages of deposition. The change in facies from sandstones to conglomerates along the basal unconformity is associated with an abrupt reduction of contact topography. Probably, a buried fault scarp provides the best interpretation of the contact in this area.

The wedge shape of the marginal fan complexes (Figs 2 and 4) apparently records progressive eastwards tilting of the hangingwall of the detachment zone during deposition. The syndepositional rotation of the basin on the fault as deduced from fanning dips in the Devonian strata is 20°. The total amount of rotation in the hangingwall from the onset of sedimentation is ≈30° (20° syndepositional rotation + ≈10° dip recorded by the uppermost Devonian strata). Across the Instelva fault, the eastwards dip of the basal unconformity is reduced to ≈20°. The reduction in dip is accompanied by a thickness decrease in the lower part of the southern margin fan complex, from more than 1 km in the footwall to ≈500 m in the hangingwall. Westwards, thickness increases gradually. In the hangingwall of the Instelva fault, a floodplain unit onlaps or interfingers with the lower part of the southern margin fan complex. Apparently, the southern margin fan complex dipped to the west at the time of deposition of the fine-grained units immediately overlying it. At the same stratigraphic level, the conglomerates of the northern margin fan complex display an eastwards onlap onto the basal unconformity. If bedding immediately above the basal unconformity is restored to a horizontal position (Fig. 10a), the basal unconformity displays a westwards dip. A change in the direction of onlap takes place across the faulted area between the Instelva and Grunnevatn faults. West of this area, onlap is towards the east. East of the Instelva fault onlap is towards the west, as displayed by the wedge geometry of the marginal fan complexes. The above observations indicate that a large-scale, rollover anticline–syncline pair developed in the hangingwall of the detachment zone during basin deposition (Fig. 17). In Fig. 4 an anticlinal geometry is evident also at high stratigraphic levels in the easternmost parts of the basin. The anticline is associated with a fanning wedge geometry displayed by the Devonian strata. The fanning wedge geometry indicates that the migration of fluvial channel sandstones and fine-grained heterolithic units towards the east and stratigraphically upwards was related to the progressive eastwards tilting of the basin floor. We infer that the rollover migrated through the basin with time, much in the way modelled by McClay & Scott (1991). A migrating rollover structure explains some of the onlap onto the unconformable basin margins, and is in accordance with large-scale extensional displacements along a W- or NW-dipping detachment. The southwards component of dip inferred from onlap relationships at low stratigraphic levels does, together with the basic asymmetry in sedimentary facies configuration, suggest that the boundary conditions in terms of tectonic control changed from early to late stages of basin deposition. This opens the possibility that the Kvamshesten Basin is a polyhistory basin, or that the fundamental basin-forming mechanism itself induced a change in the strain field during sedimentation.

Syndepositional extensional faults

Our observations strongly suggest a syndepositional origin for a number of the oblique faults desribed earlier. Evidence for syndepositional fault activity includes thickness variations across faults, rapid termination of fault displacement upwards in the stratigraphy and wedges of coarse sediment that thin away from the fault planes and intercalate with sandstones distally. We infer the offsets of the basal unconformity to represent synsedimentary basin floor topography. Also, we infer the climbs of stratigraphic boundaries associated with the Selsvatn fault system to reflect synsedimentary fault activity. To reveal the synsedimentary orientations of the faults, the basin margin must be restored to its syndepositional orientation (Fig. 11c,d). This is achieved by rotating the faults with bedding around the axis of the basinal synform, followed by rotation around a N–S axis to compensate for the eastwards tilt of the basin upon the detachment zone. The apparent strike-parallel separation observed for many of the faults in map view changes to mainly normal separation when the flank of the basinal syncline is restored. Restoration of the NE-dipping south-western basin margin to its syndepositional orientation leaves most of the faults with dips between 60° and 80°. Some are rotated to a reverse position. The steep dips of some of the faults, together with their generally high cutoff angles with bedding, indicate that the faults originated as tension fractures that started to accommodate displacement as the basin rotated upon the detachment zone. Thus, some of the intrabasinal faults may be regarded as second- or third-order faults in the terminology of Angelier & Coletta (1983). The inferred presence of a hangingwall anticline–syncline pair indicates that the basin-bounding fault had a ramp-flat geometry. McClay & Scott (1991) showed that reverse faults may develop in a basin as it passes the ramp. The faults that display reverse positions after restoration may have formed in this way. The lack of lineations from most of the faults along the south-western margin does not allow for any accurate determination of extension direction.

Restoration of the Selsvatn fault system (Fig. 11d) in a similar manner reveals four sets of syndepositional faults, apparently conjugate to each other. The displacements accommodated by the faults must have been mainly normal to provide accommodation for the excess stratigraphy preserved in their hangingwalls. The long-waved (>1 km) deflection of bedding associated with some of the faults in the Selsvatn fault system are interpreted by us as rollover anticlines, superposed on the larger-scale anticline evident in Fig. 4. As activity on the four main faults in the area must have partly overlapped in time, the faults would define an orthorhombic fault pattern with NE- and NW-striking faults, respectively, on the synsedimentary surface. An orthorhombic fault pattern (Reches & Dieterich, 1983, Krantz, 1988) comprises four mutually conjugate sets of faults and are interpreted as the product of a three-dimensional strain field. The orientations of fault planes can be used to determine the directions and signs of the principal strain axes. In the odd-axis model of Krantz (1988) the 'odd' strain axis is defined as the axis with a sign of elongation that is opposite to the other two. Correspondingly, the 'similar' axes have signs of elongation that are similar to each other, but different from that of the 'odd' axis. The intermediate strain axis and the axis which is similar to it bisect the acute and obtuse angles, respectively, between the strikes of the fault sets. The axes of symmetry that can be extracted from Fig. 11(d) are orientated approximately E–W and N–S, respectively. Thus, the Selsvatn fault system formed in a strain field characterized by E–W and N–S extension. The axis of maximum elongation was approximately E–W, parallel to the ductile lineation in the extensional mylonites below the basin. The strain field deduced from the restored Selsvatn fault system thus provides a kinematic link between synsedimentary faults in the Devonian basin and the Devonian extensional shear zone below it. In the present conception of the syndepositional tectonic framework, eastwards migration of the depocentre can be related to the progressive eastwards tilting of the basin upon the detachment zone. The stratigraphic climbs displayed by the lower boundary of the green sandstones adjacent to the Mariefjellet and Berge faults indicate that the faults affected the (south) eastwards migration of the sandy fluvial belt. Apparently, the sandy fluvial belt was trapped temporarily in the hangingwalls of the intrabasinal faults. The intrabasinal faults described above affect and are draped by progressively higher stratigraphic levels eastwards in the basin. We infer that intrabasinal fault activity migrated eastwards through the basin during the course of its deposition. Experimental work by Xiao *et al.* (1991) indicates that intrahangingwall faults within extensional wedges migrate towards the footwall with time. In the case of a ramp-flat extensional detachment, the crestal collapse of a hangingwall rollover anticline tends to migrate stratigraphically upwards and towards the detachment breakaway (McClay & Scott, 1991). We suggest that this was the case in the Kvamshesten Basin.

North–south shortening

The N–S shortening of the Kvamshesten Basin was accommodated by folding, reverse faulting and re-activation of earlier extensional faults. To the west and east of the Instelva and Blegjeskardet faults, respectively, fold trains an order of magnitude smaller than the basinal syncline are common. In the trapezoidal fault block that constitutes the footwall of the Instelva, Blegjeskardet and Kringlefjellet faults, folds of this amplitude and wavelength are generally not recognized. The axis of the basinal syncline is apparently displaced with a sinistral and dextral sense, respectively, across the Instelva and Blegjeskardet faults. We interpret the Instelva and Blegjeskardet faults to have acted as transfer faults during N–S shortening, in the way that they separated the area dominated by thrusting on the Kringlefjellet reverse fault from areas where shortening was taken up by other combinations of faulting and folding. Theoretically, conjugate sets of NE- and NW-striking extensional faults would have orientations that were favourable for strike-slip reactivation during N–S shortening. Moreover, rotation of the faults towards steeper orientations during formation of the basinal syncline would enhance the potential for re-activation. The strike-slip movements accommodated by the Blegjeskardet and Instelva faults may be explained in this way. The steep, NE- and NW-striking shear fractures reported from the basin as well as from the depositional substrate (Markussen, 1994; Osmundsen, 1996) may have formed during continued shortening, as suggested by Skjerlie (1971). Across the Instelva fault, the trend of the basinal syncline changes by $\approx 10^\circ$ in a clockwise direction (Fig. 13). Correspondingly, in the westernmost part of the basin, a number of folds and reverse faults have a north-west trend. This may be explained by rotation about a vertical axis during sinistral slip on the Instelva fault. Alternatively, the stratigraphic levels in the western parts of the basin record a NE-directed shortening that was not experienced by higher stratigraphic levels. The relationship between N–S shortening and sedimentation in the Kvamshesten Basin is, however, not unambiguous. Seranne *et al.* (1989) followed by Chauvet & Seranne (1994) inferred that the northward onlap relationship observed along the northern basin margin was produced by syndepositional N–S shortening. This interpretation requires a syndepositional, southwards dip of the basal unconformity along the northern margin. The southern margin would, in this scenario, be characterized by southwards onlap onto basement. A north- to north-eastwards component of onlap is inferred for the entire westernmost part of the basin including the southern flank of the basinal synform. Thus, the observed onlap onto basement does not seem to reflect the present synformal shape of the Devonian strata. Our profiles in Fig. 5 do not reveal any significant difference in the degree of shortening between low and high stratigraphic levels. At high stratigraphic levels in the basin, bedding is overturned in the hangingwall of a large reverse fault (see also Braathen, 1997) that crops out along the present northern basin margin. Thus, considerable shortening took place at a relatively late stage, probably after deposition of the preserved stratigraphy. Some unconformities are re-interpreted as related to rollover formation rather than to syndepositional N–S shortening (Osmundsen, 1996). In the Hornelen Basin, discontinuities interpreted as internal unconformities were rejected by Wilks & Cuthbert (1994). In the Kvamshesten Basin, interpretation of discontinuities in the Devonian stratigraphy that would conform to the internal unconformities suggested by Chauvet & Seranne (1994) is generally ambiguous. Some of the proposed unconformities have been rejected (Osmundsen, 1996). Thus, some doubt exists whether shortening commenced during deposition. The syndepositional Selsvatn Fault System represents a strain field that was characterized by E–W and N–S extension. Thus, if shortening commenced during basin deposition, it cannot have been continuous throughout the basin history.

DISCUSSION

Models for Devonian basin formation in western Norway

Steel (1976) ruled out climate and source rock variation as major controls in the western Norwegian Devonian basins. Thus, the facies architecture of individual basins should closely reflect the tectonics during deposition. With respect to the general facies architecture, the Kvamshesten Basin shows similarities with the Hornelen (cf. Steel & Aasheim, 1978; Steel & Gloppen, 1980) and Solund (Nilsen, 1968; Steel *et al.*, 1985 Seranne, 1988) basins. All three basins display large, streamflow-dominated fan complexes along their southern margins, whereas the northern basin margins have variably been the locus of mass-flow type deposition (Steel *et al.*, 1985; this work) on smaller fans. In the model for the Hornelen Basin by Steel & Gloppen (1980), the southern and northern basin margins were principally different in nature, and dominated by normal and strike-slip faulting, respectively. Following the identification of the low-angle normal faults (Hossack, 1984; Norton, 1986), it was argued that the detachment faults that controlled Devonian basin sedimentation were scoop-shaped (Hossack, 1984; Seranne *et al.*, 1989; Chauvet & Seranne, 1994; Wilks & Cuthbert, 1994). In these interpretations, the scoop-shaped detachment faults were characterized by a normal slip eastern segment, giving way to strike slip segments at the northern and southern margins, respectively (Hossack, 1984). This would explain the marginal conglomerates and the central belt of fluvial sandstones observed in the Hornelen Basin as well as the Kvamshesten Basin and also the lateral stacking of fanglomerates along the basin margins (Steel & Gloppen, 1980). However, a problem with these models is the consistent asymmetry of the Devonian basins, in particular the Kvamshesten and Solund basins. In the models by Hossack (1984) and Wilks & Cuthbert (1994) both the southern and the northern basin margins were bordered by strike-slip fault segments from the onset of deposition. Thus, there would be no principal difference between the northern and southern basin margins except in the sense of displacement. Our data from the Kvamshesten Basin indicate that a principal difference did exist between the northern and southern basin margins, at least at an early stage. This suggests that a change in boundary conditions took place during sedimentation. Either there was a re-arrangement in the pattern of basin-bounding faults during sedimentation or the kinematics of the basin-bounding faults changed, or both.

The inferred scoop shape was given different explanations by the various authors. Hossack's (1984) model was based mainly on the present basin margins and interpreted the basin bounding fault as a re-activated thrust where the strike-slip segments were lateral ramps inherited from the original thrust geometry. Milnes *et al.* (1988) showed, however, that the Nordfjord–Sogn detachment zone cross-cuts the Caledonian tectonostratigraphy. Wilks & Cuthbert (1994) argued for a basin-bounding fault that had a primary scoop-shape, analogous to corrugated detachments described from the Basin and Range Province (see Friedman & Burbank, 1995). Chauvet & Seranne (1994) argued that the basin-bounding faults acquired their scoop shape through progressive, synsedimentary folding around E–W trending axes. They presented a model that attempted to explain the parallelism between the mylonitic lineation and fold axes in the footwall of the detachment zone as well as the proposed unconformities in the Devonian basin fill. Chauvet & Seranne (1994) suggested that during Devonian basin formation, the axes of maximum and intermediate compressive stress had values close to each other, i.e. they were both compressive, and orientated vertically and N–S, respectively. σ_3 was horizontal, extensional and orientated in an E–W direction. The basin-controlling fault would be folded around a fold axis parallel to the W-plunging mylonitic lineation in the WGR. The implication would be a basin that was symmetric with respect to the mylonitic lineation as well as with respect to the basinal syncline. Our profiles in Fig. 5 are constructed normal to the basinal synform. The profiles show both a pronounced asymmetry in the organization of sedimentary facies units as well as a marked diachronism between the northern and southern basin margins. Thus, in our view, the basinal synform axis does not represent an axis of symmetry. Rather, the asymmetry of sedimentary facies indicates that the early basin history did not conform to a symmetric tectonic model.

Hartz & Andresen (1997) argue that the Hornelen Basin initiated as an E–W-trending graben, analogous to the orogen-normal grabens of the Tibetan Plateau. In their model, the earliest stages of basin formation was controlled by N–S extension parallel to the orogenic front. The orogen-parallel extension was followed by gradual E–W and N–S extension, as a function of stress axis permutation when crustal thickening was relieved by orogenic collapse. After deposition, N–S shortening commenced due to sinistral plate movements between Baltica and Laurentia. Theoretically, the southwards component of tilt of the floor of the Kvamshesten Basin could be related to an E–W- or NW-trending, asymmetric graben formed normal to the orogenic front. Several NW-striking faults in the vicinity of the basin are cut and displaced by NE-trending synsedimentary faults (Osmundsen, 1996). As their relations to the Devonian unconformity are generally indeterminable, they may pre-date deposition in the Kvamshesten Basin. The southern margin fan complex remained a major depositional system through the preserved stratigraphy. If the fan complex was controlled by a W- or NW-striking fault at an early stage, this fault should theoretically have developed into a transfer fault at the onset of top-to-the-west extension. Such a fault would cut the Caledonian tectonostratigraphy south-west of the basin and produce displacements comparable to the length of the basin. This does not appear to be the case. Thus, a model like that of Hartz & Andresen (1997) cannot readily be adapted for the Kvamshesten Basin.

A model for the Kvamshesten Basin

In our discussion of a model for the Kvamshesten and other Devonian basins we focus on basinal asymmetry with respect to the mylonitic lineation below the basin, as well as with respect to the main synclinal axis. In the Kvamshesten Basin, the southern margin fan complex is clearly the thickest of the two marginal fan complexes, and our profiles (Fig. 5) indicate a significant southwards component of tilt during early stages of deposition. The geometries of fans at high stratigraphic levels indicate a bulk transport direction from the south-east towards the north-west on the southern basin margin. The southwards component of rotation accommodated by the Kvamshesten Basin provided accommodation for the lower part of the southern margin fan complex at a time when the northern margin was in an updip position characterized by bypass or erosion (Fig. 17). As the northern basin margin was draped with sediment, the northern margin fan complex developed as a sedimentary wedge similar to the southern margin fan complex. We suggest (Fig. 17) that sedimentation in the northern margin fan complex was triggered by the formation of a NW-trending transfer fault. From this stage, the basin had a 'scoop' shape and coarse debris was transported into the basin from both sides. The northern and southern basin margins would be principally different because the dip of the NW-trending transfer fault would be steeper than the dip of the normal fault bounding the basin in the south-east. A steeper fault on the northern margin would account for the abundant debris flow deposits (Steel *et al.*, 1985) encountered in the northern margin fan complex. The northern margin fan complex probably remained subordinate in thickness compared to the southern margin fan complex, as the latter continued to be a major depositional system throughout the preserved basin stratigraphy. The E–W direction of maximum elongation inferred from the Selsvatn fault system is in accordance with an eastwards rotation of the basin. Thus, the stratigraphy at medium stratigraphic levels must record a change in subsidence pattern from a half graben that accommodated a significant component of southwards rotation to a half graben that rotated mainly towards the east (Fig. 17). The stratigraphic interval in question records firstly the apparent shift in the locus of floodplain deposition from a relatively widespread configuration in the (preserved) basin to a position restricted to the northern margin. Second, it records the progradation of coarse-grained fans from both basin margins towards the central areas. The shift of the locus of floodplain deposition has been thought to reflect episodes of subsidence in extensional basins (Alexander & Leeder, 1987; Leeder & Gawthorpe, 1987). Floodplains as well as channel belts will have a tendency to migrate towards the area of maximum subsidence. Tentatively, the shift in position of the floodplain referred to above can be explained by the change in slip directions on the basin-bounding faults. If the direction of extension changed from north-west to west, slip on the relatively steep northern margin fault would change from dominantly dextral to oblique normal. The northern basin margin would thus experience an increase in subsidence relative to the southern margin. This may have caused the migration of the floodplain towards the northern margin. Eventually, the increased subsidence would allow increased fan progradation from the northern margin. The stratigraphic interval referred to above suggests a major period of subsidence in the entire basin, as major fan segments prograded from the northern as well as the southern basin margins following the northwards shift of the floodplain. At high stratigraphic levels, the basin was extending in E–W as well as N–S directions. At this stage (Fig. 17d), the basin experienced top-to the west displacement and eastwards rotation. The locus of floodplain deposition had apparently shifted again to be located mainly along the south-eastern basin margin. This shift cannot be explained by a line of argument like that above, as the fault on the south-eastern margin must have undergone a change from mainly normal to sinistral/normal. Thus, the southern margin would have undergone a decrease in subsidence per unit of extension. Possibly, the locus of floodplain deposition was controlled by the intrabasinal faults at this stage.

Most of the shortening experienced by the Kvamshesten Basin took place after deposition of the preserved stratigraphy. This is evident by the rotation of bedding at high stratigraphic levels on the southern margin to dips of 45° and more, and by the inversion of bedding at high stratigraphic levels on the northern margin. Thus, the basinal syncline represents the relatively late stages of contraction responsible for most of the shortening in the Kvamshesten Basin. Within the model framework outlined above, the lack of symmetry in sections normal to the basinal syncline is explained by the oblique relationship between the originally NW-dipping basin-bounding fault and the E-plunging fold axis.

The Dalsfjord fault sharply truncates already folded Devonian strata. The cross-cutting relationships between the Dalsfjord fault and the Devonian basin added further asymmetry to the structural section, as the synsedimentary basin margins had rotated out of their original orientation by folding prior to slip on the Dalsfjord fault. The age of incipient displacement along the Dalsfjord fault is unknown. The W-plunging scoop shape of the fault indicates that it experienced N–S shortening, although less than the Devonian basin (see also Torsvik *et al.*, 1986). Juxtaposition of Devonian rocks with detachment mylonites was completed during late slip along the Dalsfjord fault. The amount of late slip is uncertain due to unknown amounts of juxtaposition at depth during synsedimentary slip on the original basin-bounding fault. It is possible, however, that the entire juxtaposition is due to slip on the Dalsfjord fault, in which case more than 13 km of displacement post-dated the preserved basin stratigraphy. Tentatively, slip on the Dalsfjord fault may have commenced in the late Devonian/early Carboniferous, prior to complete cessation of N–S shortening. Permian and Mesozoic movements along the fault (Torsvik *et al.*, 1992; Eide *et al.*, 1997) show that movement continued past the time-window represented by the Devonian basins.

The Devonian basins of western Norway: products of combined extension and strike-slip?

The Hornelen Basin does not display the kilometre-thick fan complexes that are prominent in the southern basins. The exposed levels of the basin thus display a more symmetrical facies configuration with conglomerate fringes along the basin margins and a large central area occupied by sandstones. The geometry of the basin at depth is largely unknown, although low stratigraphic levels are preserved on skerries and islands along the basin's unconformable western margin (see Hartz & Andresen, 1997). Palaeocurrent directions in the Hornelen Basin are generally westwards in the central basin area, and towards the central basin area from the southern and northern margins (Steel & Gloppen, 1980). In summary, the Hornelen Basin is more symmetric about the W-plunging lineation in the ductilely deformed rocks below the basin than are the southern basins. In the Solund basin, the fanglomerate complex of the basin's south-eastern margin is banked against the NW-dipping Solund fault. Palaeocurrents in the conglomerates as well as in minor sandstone bodies were mainly towards the NW, consistent with transverse drainage and deposition away from a NW-dipping fault (Nilsen, 1968). Apparently, the thickest and coarsest fanglomerate units in both the Solund and Kvamshesten Basins were sourced from drainage basins located on the SE side of the basins, developed in the footwalls of low- to moderate-angle, NW-dipping faults. The original basin-controlling faults were thus oblique to the W- to WNW-plunging lineation observed in the detachment mylonites directly below the basins. Therefore, on a regional scale (Fig. 1), intrabasinal asymmetry apparently increases from the Hornelen Basin in the north to the Solund Basin in the south. If tectonics was the main control on basin formation (Steel, 1976), this points towards a variation in the geometry and/or slip directions of the basin-controlling faults.

The ductile lineations in the mylonites of the Nordfjord–Sogn Detachment Zone are oblique to the NE-trending enveloping surface of the shear zone on a regional scale. Thus, displacement in the detachment zone was transtensional rather than dip-slip extensional (Krabbendam & Dewey, in press). Moreover, the azimuth of the ductile lineation swings from a WNW orientation east of the Solund Basin to a WSW orientation north of the Hornelen Basin close to the Møre–Trøndelag Fault Zone (MTFZ) (Seranne *et al.*, 1991; Chauvet & Seranne, 1994; Krabbendam & Dewey, in press). North of the Møre–Trøndelag fault, it swings back to a north-west plunge in the Roan Window area (Krabbendam & Dewey, in press). They concluded that the MTFZ was active as a sinistral shear zone during detachment faulting and exhumation of the Caledonian eclogites of the WGR. A critical point is whether sinistral shearing was contemporaneous with Devonian sedimentation, or occurred at a later stage. Recent low-temperature Ar–Ar geochronology and thermal modelling on feldspars indicate that the rocks of the WGR cooled from $\approx 285\,^{\circ}\mathrm{C}$ to below $150\,^{\circ}\mathrm{C}$ prior to 350 Ma (Eide *et al.*, 1998). The anticlockwise deflection of the extensional lineation as well as the folding about E–W axes should therefore pre-date 350 Ma. The change in syndepositional tilt direction inferred by us from the Kvamshesten Basin suggests a rotation of the direction of maximum elongation from north-west to west during basin formation. The hangingwall of the detachment zone experienced a minimum of 50–100 km of north-west to west translation in the Devonian. Thus, the initial NW-directed extension direction apparently recorded by the Kvamshesten Basin represents deformation that took place when the basin was in a position tens of kilometres to the south-east of its present location. Thus, the anticlockwise change in tilt direction displayed by the basin may reflect the same strain gradient as the anticlockwise rotation displayed by the ductile lineation in the detachment zone and WGR. Both relations are compatible with sinistral shearing along the MTFZ. If the basin-controlling faults formed with orientations approximately perpendicular to the local direction of maximum elongation, then the array of basin-forming faults would display north-west dips in the Solund and Kvamshesten areas, and west to south-west dips in the Hornelen and Møre-Trøndelag areas (Fig. 18). For the Kvamshesten Basin, this would imply an early phase of north-westwards extension, gradually taken over by west-northwest extension as the basins moved closer to the MTFZ. An early south-eastwards tilt of the basin floor would correspondingly be taken over by tilting towards the east-southeast and by a change in movement direction for the basin-bounding faults. The marginal fan complexes in the individual basins would thus be thicker in the south-east for both the Solund and Kvamshesten basins. Tentatively, the generally NE-trending faults that dominate in the basin's depositional substrate and that were synsedimentary at low stratigraphic levels may represent an early strain field dominated by north-west extension. Correspondingly, the orthorhombic Selsvatn fault system may reflect the E–W extension experienced by the basin at a later stage,

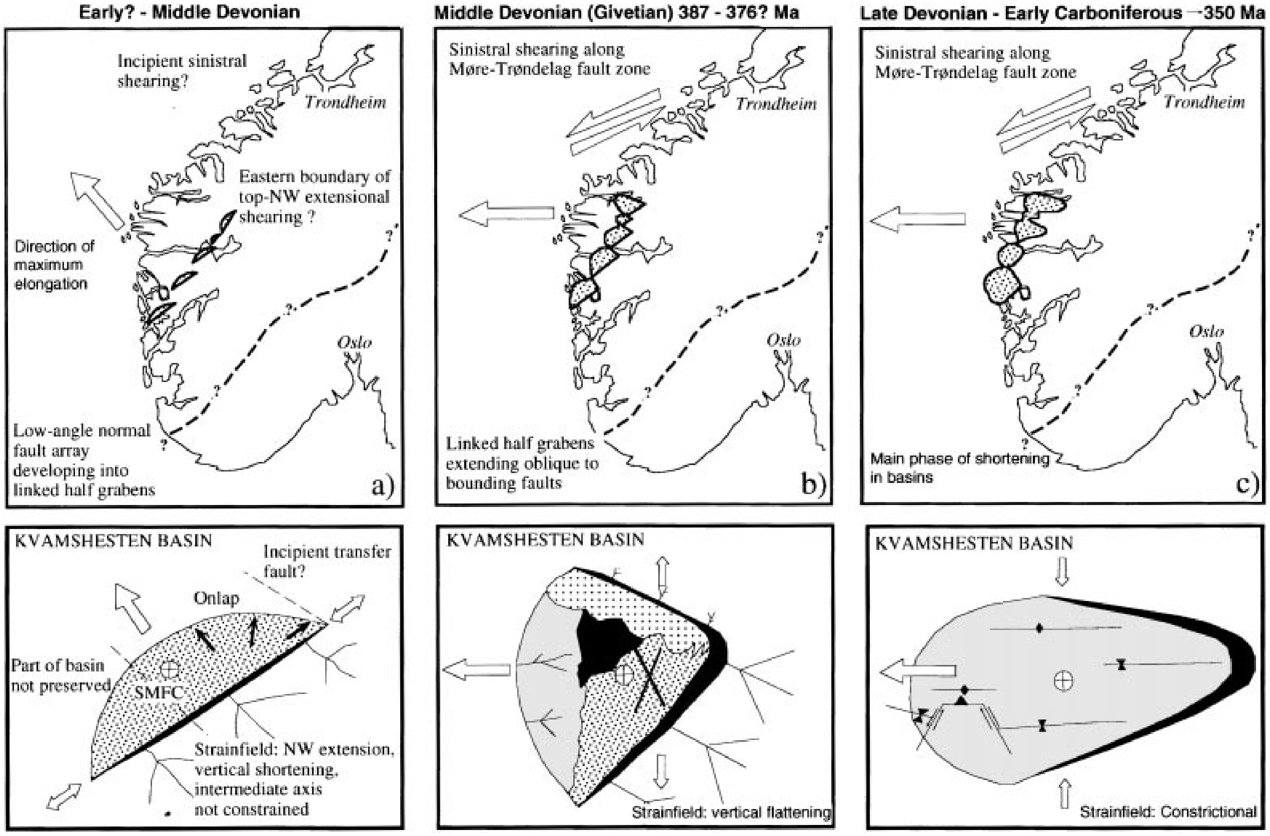

Fig. 18. Tentative model for Devonian basin development in western Norway. The model involves strain partitioning between the mainly extensional Nordfjord–Sogn Detachment Zone and the mainly sinistral Møre–Trøndelag Fault Zone. The model is based on observations presented in this paper, as well as on regional data and inferences by Chauvet & Seranne (1994) and by Krabbendam & Dewey (in press). (a) Initial configuration of basin-bounding faults. The direction of maximum elongation was north-west for the southernmost basin area. Correspondingly, basin-bounding faults were NE-striking in the Solund and Kvamshesten areas. It is not obvious whether any extension-normal shortening affected the basins at this stage. In the Kvamshesten Basin, this stage corresponds to stage (a) of Fig. 17. (b) The basins were transported closer to the principal zone of orogen-parallel sinistral shearing. The direction of maximum elongation changed to a more westward orientation, as evidenced by the present W-plunging lineation in the footwall of the detachment zone, as well as by intrabasinal extensional faults (Selsvatn fault system). Intermediate elongation was positive and north–south, contrary to the continuous, negative north–south elongations suggested by previous authors (Chauvet & Seranne, 1994; Krabbendam & Dewey, in press). We suggest that the strain fields experienced by the basins may not have been entirely identical to the strain fields experienced by the footwall of the detachment zone (see text). In the Kvamshesten Basin, this stage corresponds to stage (d), possibly also to stage (c) in Fig. 17. (c) The main phase of north–south shortening affected the basin after deposition of the preserved stratigraphy, as the basins were transported closer to the Møre–Trøndelag Fault Zone. The basin was still extending in an east–west direction.

as the basin was transported into areas closer to the principal sinistral shear zone. Eventually, the basins would be juxtaposed with extensional mylonites that recorded the later stages of transport. The configuration of sedimentary facies in the basins would, however, preserve a record of the tectonic development from the onset of sedimentation. Among the preserved basins, the Solund Basin displays a geometry and facies distribution that corresponds most closely to the earliest stage of basin formation outlined above (Fig. 18a). The Kvamshesten Basin records both early, NW- and later W-directed extension (stage a and b in Fig. 18). The Hornelen Basin is apparently more symmetric about the lineation in the footwall and may record mainly stage (b). The sedimentary facies configuration in the preserved basins are therefore interpreted to reflect their position with respect to the MTFZ, and thus a strain gradient related to sinistral shearing along the orogen.

The transtensional model by Krabbendam & Dewey (in press) predicts plane strain followed by constrictional strain. From our data, it is not obvious whether the basin experienced early, syndepositional shortening. At a high stratigraphic level, the strain field was three-dimensional (Fig. 11d), characterized by positive elongation both in the *X* and *Y* directions (Osmundsen, 1996). A synsedimentary strain field characterized by vertical flattening has recently been documented also from low stratigraphic levels in the Hornelen Basin (Hartz & Andresen, 1997). Thus, E–W and N–S elongation accompanied basin formation on a regional scale. This is not compatible with models that predict continuous N–S shortening of the basins during sedimentation. In the hangingwall of the detachment zone, N–S shortening must either have occurred in pulses separated by periods of N–S extension or it must entirely post-date basin formation. This points towards a strong partitioning between extensional and strike-slip deformation or a time lag between the onset of north-westwards extension and the onset of sinistral shearing. Also, while the WGR was being unloaded by extension, the basin areas were increasing their load by recieving large amounts of sediment. Thus, the local strain field in the hangingwall of the detachment zone may not have constituted a blueprint of the strain field in the footwall, that was undergoing contemporaneous unloading. A model involving a large-scale sinistral component of deformation rather than continuous dip-slip extension explains several of our observations in the Kvamshesten Basin, and is compatible with observations on a regional scale. In particular, it provides a better explanation for the asymmetry of individual basins, the regional variation in asymmetry between the basins, and the oblique relationship between the basinal fold axis and the sedimentary facies distribution.

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