Devonian Tectonic Deformation in the Norwegian Caledonides and Its Regional Perspectives

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Late-Caledonian megascopic folds deforming the Old Red Sandstone sequences of southern Norway are mostly synclines of E–W to NE–SW trend and E to NE plunge. Thrusts along the eastern and southern margins of several ORS areas, and stretching lineations, denote approximate southeastward translations of the sequences from their basinal sites. This contractile movement occurred principally along rejuvenated, syn-depositional, planar or listric-style extension faults.

Development of the basins took place during the imposition of a fundamental NW–SE to NNW–SSE crustal extension following the major Scandian, Silurian orogenic phase. This was also influenced by an orogen-parallel sinistral mega-shear from Svalbard through northern Britain to the Appalachians which assisted in producing a transtensional regime in southern Norway. Thus, during ORS basin development and sedimentation a subordinate dextral strike-slip component has acted in combination with the basic extensile field. During late Devonian, probably Frasnian time, this transtensional regime was replaced by a SE-directed compression, and partly transpression, so producing the macrofolds, late ductile thrusts and other structures which are traceable far outside the confines of the ORS districts.

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Introduction

The Old Red Sandstone (ORS) basins of southern Norway have received much attention in recent years with emphasis placed on establishing detailed stratigraphies and facies sequences, and interpreting these in terms of palaeography within a framework of syn-depositional tectonism (Bryhni 1964, 1975, 1978, Nilsen 1968, Steel 1976, Steel & Gloppen 1980). In consequence of this, sedimentological studies have prevailed and comparatively little work has been done on aspects of post-depositional tectonic deformation. The Downtonian to Middle Devonian sediments do, in fact, display variable effects of what is generally termed late-Caledonian tectonism (Roberts & Sturt 1980), which is an important element in the overall development history of the mountain belt. In this synthesis, the most significant traits of this tectonic deformation are outlined, and discussed briefly in a wider context of the waning phases of Caledonide orogenic evolution. Details of stratigraphic sequences and lithologies are contained in the cited publications, including a recent review article (Steel et al. 1983), and will therefore not be repeated here.

Tectonic structures in the different ORS basins

A feature common to the 8 or 9 ORS basinal sequences is their deformation and dissection by open folds and faults. Many of the sequences have also been detached along thrust surfaces, mostly with evidence of east to southeast translations, although the extent and magnitude of the thrusting is generally not known in any detail.

The Lower to Middle Devonian sequences of *Vestlandet* (western Norway) occur in 4 main areas (Fig. 1). The axial trends of the folds which deform the ORS rocks vary from NE–SW at Solund (Nilsen 1968) through ENE–WSW in the Hornelen and Kvamshesten basins (Bryhni 1964, Höisæter 1971, Bryhni & Skjerlie 1975) to E–W at Haasteinen (Kolderup 1925), with axial

Fig. 1. Locations of the main areas of Old Red Sandstone sediments in southern Norway. The ruled area represents the approximate extent of the Caledonian nappes and autochthon. The remaining, white areas are Precambrian crystalline basement, probably partly allochthonous (Caledonian) in the northwest.

plunges consistently towards the E to NE quadrant (Fig. 2); axial surfaces are either vertical or dip steeply towards NW–N. Major cataclastic faults displacing the ORS rocks show main trends of NE–SW and c. NW–SE, while locally N–S fractures are of importance. Some basins are also fault-bounded, e.g. Hornelen and Haasteinen.

Thrust displacements of the ORS complexes have been reported from all the Vestlandet Devonian basinal areas, although the westernmost contacts of these rocks with their crystalline substrates generally show undisturbed angular–unconformable relationships. At *Solund* a 15° thrust contact delimits the southeastern margin of the ORS rocks. Above a thin basal mylonite with NW–SE quartz grain elongation lineation, conglomerate pebbles are strongly deformed within a zone of 2.5 km mappable width (Nilsen 1968). Pebble lineation is NW–SE, with NW plunge, contrasting strongly with the SE-dipping bedding in the conglomerate. A comparable, pervasive, NW–SE pebble lineation has also been reported from the outermost islands in the Solund district (Indrevær & Steel 1975). This may well relate to a subsurface thrust zone, and quite possibly an extension of the basal Solund Thrust. Dip-slip extensional faults parallel to the Solund Thrust, bedding-plane slippage faults and local, NE–SW, strike-slip faults are other deformational structures present in the Solund ORS district (Nilsen 1968). Minor thrusts occur in other parts of the Solund area, some with thin ultramylonites (Furnes & Lippard, in press); these same authors describe a lowest greenschist facies metamorphic paragenesis and schistosity in Devonian trachytic lavas. A thrust origin was also advocated by Kolderup (1926) for lensoid gabbro bodies occurring within Devonian conglomerates in the Hersvik area, although other interpretations have since been proposed – Nilsen (1968) favoured an intrusive origin, as gabbro sills, whereas Bryhni (1976) considered the gabbro as possibly representing a debris flow deposit. Recent investigations (D. M. Ramsay, pers.comm. 1982), including the recognition of a basal mylonite, favour a thrust emplacement for this gabbro. Cumulative thrust displacement of the Solund ORS sequences as a whole may be several tens of kilometres (B. A. Sturt, pers.comm. 1982).

At *Kvamshesten* (Fig. 1) the folded Devonian rocks are truncated by a flat-lying thrust delimiting the southern, eastern and northeastern boundaries of the ORS outcrop (Bryhni & Skjerlie 1975), with a "strongly mylonitized zone some tens of metres in thickness" (Höisæter 1971) marking the thrust contact with subjacent metasediments. Few details are yet available on this thrusting; those reported are ambiguous with Skjerlie (1971) noting both northward and northeastward directed thrusting, whereas eastward displacement is favoured by Nilsen (1968). An eastward translation seems the more likely, at least for the main fairly ductile detachment and transport of the ORS rocks from their basinal site, and strain reduction to mylonite at the base of the sequence. The thrust surface in the eastern part of the district has been referred to as a probable sole thrust by Bryhni & Skjerlie (1975). Judging from the map-picture (Höysæter 1971, Bryhni & Skjerlie 1975) which shows the thrust, towards the west, also forming the floor to a sheet of Precambrian plutonic rocks and Lower Palaeozoic schists below the unconformably overlying ORS sediments, this characterization would appear valid. Another feature of interest is that some of the faults cutting the ORS rocks do not transect the mylonitic thrust zone, whereas other, younger fractures penetrate across the thrust into the basement. The small *Haasteinen* basin just north of Kvamshesten (Fig. 1) also exposes a thrust contact along its southeastern margin (Kolderup 1925); no structural details are available from this area at the present time.

ORS sediments of the *Hornelen* basin are fault-bounded along their northern and southern margins, and displaced by thrusting in the east. Syndepositional movement along the faults, partly dextral strike-slip, has been considered an important factor in the sedimentation history of this basin (Bryhni 1964, 1978, Steel 1976, Steel et al. 1977, Steel & Gloppen 1980). Structural data from the sole thrust (Bryhni 1978) contact zone are few, although mylonitization features and neocrystallization of quartz, calcite and epidote have been reported by Bryhni (1964). In addition, mudstones adjacent to the marginal faults are strongly cleaved. In contrast to the situation at Kvamshesten, some of the folds in the southern part of this basin appear to deform the basal thrust-fault (Bryhni 1978, fig. 1), indicating at least a local continuation of folding after thrust detachment and movement.

Further north, in the coastal region of Trøndelag and Nordmøre, ORS sediments occur primarily on *Hitra* and *Fosen,* and on islands adjacent to *Smøla* (Fig. 1). The structural trait common to all these sequences is their deformation in a NE–SW to ENE–WSW trending syncline (Siedlecka & Siedlecki 1972, Siedlecka 1975, Fediuk & Siedlecki 1977) (Fig. 2). It is possible that the synclines recorded in the different areas were once part of a single structure, now transected and displaced by faulting (Steel et al. 1983). Principal fault trends in this district are NW–SE, N–S and NE–SW (Fig. 2). On Hitra a high-angle reverse fault cuts out part of the southeastern limb of the Hitra syncline against the pre-ORS basement. Apart from this example, no other cases of post ORS tectonic inversion are known from this district. Also on Hitra, a spaced cleavage paralleling the axial surfaces of mesoscopic NE–SW folds is present in some mudstones, with carbonate concretions showing rotation into the plane of anisotropy (Roberts 1981). N–S trending kink-bands of westerly downstep and a north-dipping crenulation cleavage are minor tectonic structures occurring in the ORS on this same island.

In the southeastern parts of the Trondheim region the Devonian deposits at *Røragen* were deformed during two phases of folding, the main structure being a syncline of E–W trend and easterly plunge. Minor NW-facing folds and local NW-directed thrusts constitute secondary structural elements; these deform a very low grade lepidoblastic fabric which is present in some of the pelitic lithologies (Roberts 1974). Faults show NW–SE and NE–SW trends and probably represent rejuvenated syn-depositional structures (Holmsen 1963, Jakobsson 1978).

The *Oslo basin* of southeastern Norway exposes Ludlow–Downtonian red-

Area/basin	Main macrofold	Fold trend (& plunge)	Faults		Thrusts	Foliate and linear elements
			Syn-sedimentary	Main post-sed. trends		
Solund	Anticline	NE-SW (NE)	E-W in north, ?dip-slip. NE-SW in SE, ?dip-slip	NE-SW NNW-SSE	In SE. Thrusting towards SE. Basal mylonite.	Local schistosity in lava and pelite. Later crenulation cleavage. NW-SE pebble & min. lineation.
Kvamshesten	Syncline	ENE-WSW (ENE)	E-W in north, oblique-slip. ?ENE-WSW in south	NE-SW NW-SE	In S, E & NE. Thrusting towards SE-?E. ?Late movem. towards NE-N. Basal mylonite	None reported
Haasteinen	Syncline	E-W (E)	Not known, but assumed	NE-SW NW-SE N-S	In SE-E & NE. Direction not known, assumed SE-E.	None reported
Hornelen	Syncline	ENE-WSW (ENE)	E-W in north, strike/oblique-slip. E-W/NE-SW in S, dip-slip	NE-SW NW-SE N-S	In E & SE. Direction uncertain. Probably SE-E. Mylonite	Cleavage in mudstones. Nothing else reported.
Smola Islands	Syncline	NE-SW (NE)	?NE-SW in north, slip unknown. SE contact unknown	NE-SW NW-SE	None exposed	None reported
Hitra	Syncline	ENE-WSW (ENE)	NE-SW in north, slip unknown. NE-SW in south	NW-SE NE-SW E-W N-S	None, but high-angle reverse fault in south.	Local spaced cleavage ax.-surf. to folds. Later cren. cleavage in pelites.
Fosen	Syncline	NE-SW (NE)	Probable, but no data available.	NE-SW NW-SE N-S	None exposed	None reported. Conjugate fractures in pebbles.
Roragen	Syncline	E-W (E)	NW-SE in NE, ?dip-slip. NW-SE to E-W in SW, ?dip-slip.	NE-SW NW-SE	No major thrust exposed. Minor NW-directed thrusts.	Local schistosity (phyllites). Late NE-SW minor folds. Minor shears.

Fig. 2. Summary of structural data from the main ORS basins and areas in Norway. The information is culled from the papers cited in the text.

-bed sequences which are folded in Jura-style structures along E–W to NE–SW trends (Strand 1972, Steel et al. 1983). Folds are tighter towards the north where reverse faults transect the succession; these faults become shallower southwards (Bockelie & Nystuen 1983). In general, this fold- and thrust-shortening in the Oslo area is taken up by décollement along pelitic horizons – a characteristic feature along other parts of the Caledonian front.

Outside of the presently exposed ORS basin areas, biostratigraphic control on the age of the Caledonoid tectonic structures is of course lacking. There is no reason, however, to doubt Vogt's (1928) contention that structures belonging to this late-Caledonian deformation phase are to be found throughout the length of the Norwegian Caledonides. Open folds and fault sets which deform the ORS rocks in west Norway, in many cases can be traced inland for considerable distances, and it is considered likely that the synformal 'Faltungsgraben' and Bergen arc structure also belong to this orogenic phase. Similarly, the NE–SW Tyin–Gjende Fault of the Jotun region (Battey & McRitchie 1973, Emmett 1982) is also accorded a Devonian age (M. Heim, pers.comm. 1981), while in the Hardangerfjord region late, open, NE–SW macrofolds and normal extension faults (Naterstad et al. 1973) may relate to this late-Caledonian event. Further north in the Caledonides, several of the orogen-transverse basement culminations, e.g. in the Grong district, are also probably Devonian in age.

Timing of deformation

Traditionally, the folds, related faults and slightly later thrusts which affect the ORS sequences of southern Norway have been ascribed to the *Svalbardian* orogenic phase of Vogt (1928). This lowermost Upper Devonian (Frasnian) event was established from investigations on Spitsbergen and Bjørnøya where faunal control is more than adequate; on Bjørnøya, Upper Devonian sediments lie unconformably above folded Middle Devonian and pass conformably up into the Carboniferous. Vogt (1928, 1933) noted the strong similarity of the folding, in its style and character, to that seen in the Norwegian ORS successions, as well as in parts of the Scottish ORS, and introduced the term 'Svalbard folding' or 'Svalbard orogenesis' for this widespread event.

Constraints on the age of the deformation on the Norwegian mainland are less precise and more indirect than on Svalbard. Faunas in Upper Palaeozoic sediments in the Oslo region, overlying folded Siluro-Downtonian, indicate a Middle Carboniferous age for the oldest fossiliferous rocks (Olaussen 1981). Much further afield, undeformed mafic dykes on Ytterøy, Trondheimsfjorden (Priem et al. 1968) and Varangerhalvøya, Finnmark (Beckinsale et al. 1975), have also yielded uppermost Devonian intrusive ages. Elsewhere in northern Norway, where Devonian sediments are nowhere exposed, K-Ar studies have revealed a Lower Carboniferous weathering profile on the island of Andøya (Sturt et al. 1979). Thus, for mainland Norway, Vogt's Svalbardian event can be placed somewhere in the late Devonian. Although a Frasnian age is likely, the event need not have been perfectly synchronous everywhere; diachronism of orogenic deformation is indeed a hallmark of the Caledonian mountain belt. In recognition of this it may therefore be justifiable to adopt local names for this post-Middle Devonian deformation, e.g. *Røragenian* event for eastern Norway (Roberts 1974).

An exception to this general pattern of late Devonian deformation appears to obtain in the Oslo area. There, the tectonism affects the marine Silurian succession as well as the conformably overlying red-beds, and is essentially the diachronous end-stage of the major Scandinavian or Scandian (mid to late Silurian) orogenic event. This deformation, in the Oslo region, could well be Gedinnian or Siegennian in age rather than late Devonian (cf. Roberts 1974). If so, it would correlate in time with ORS molasse sedimentation in the several intermontane basin areas further to the northwest within the already deformed and uplifted mountain chain.

Basin development and tectonic deformation in a regional context

GENERAL ASPECTS

Recent studies of the west Norwegian ORS basins have confirmed Bryhni's (1964) thesis of a close relationship between ORS sedimentation and tectonism, and led to refinements in the concept of basin development in a tectonic regime involving a combination of strike-slip and dip-slip motions (Nilsen 1968, Steel 1976, Steel & Gloppen 1980). In this general model, most of the basins provide evidence of growth by lateral accretion with the depocentre migrating east- to southeastwards through time. Sediment transport of the basinal axial deposits was mainly directed towards west or northwest. Similar evidence of tectonic control over sedimentation has emerged from work in coastal Trøndelag and at Røragen (Siedlecka & Siedlecki 1972, Siedlecka 1975, Roberts 1974, Jakobsson 1978).

Prior to the establishment of this broadly extensional or transtensional (Harland 1971) regime in Devonian time, the Brito-Scandinavian Caledonides and their East Greenland counterpart evolved from the final cratonic suturing of the Laurentian and Baltoscandian plates in a major phase of crustal contraction. This Scandian crustal shortening involved southeastward nappe translations of hundreds of kilometres in the Norwegian part of the belt, with the shortening vector swinging towards south in the Oslo district. Nappe stretching lineations, c. NW–SE, and internal foliations were then deformed by major NE–SW folds, with antiforms providing the loci of many of the tectonic windows which occur throughout the orogen; and subsequent to this a period of crustal distension was initiated, aided by gravitational sagging of the tectonostratigraphically thickened uppermost crust (Roberts & Sturt 1980). It is important to remember, however, that at the same time as this NW–SE extensional regime was coming into play in tectonically higher and internal parts of the orogen, in the southeastern frontal districts the red-beds of the Oslo region were still being deposited or were just about to suffer their Scandian tectonic contraction.

REGIONAL AND OROGENIC FACTORS

The surface-crustal extension which led to the production of the ORS basins was itself influenced by two main factors, one of orogenic proportions and the other of more regional character. The regional factor pertains to the existing Scandian, post-thrusting, macrofold pattern and associated dislocations in southern Norway which, it is submitted, would be expected to have controlled the generation of the extension faults bordering the ORS molasse basins. Support for this is seen in minor dip-slip faults outside of the ORS basins, associated with the gravitational vertical-shortening stage of the Scandian orogeny: in most cases these faults strike parallel to the c. NE–SW axial trend of the macrofolds. The second factor, of a more orogen-wide magnitude, relates to the imposition of a palaeomagnetically and geologically defined wrench fault regime throughout the Caledonian–Appalachian belt (Harland 1973, Storetvedt 1973, Morris 1976, Kent & Opdyke 1979) following the final, late Silurian, cratonic suturing. The principal strike-slip megafracture here is considered to have extended from Svalbard south-southwestwards to northern Britain and into the northern Appalachians, and involved sinistral displacement of some 1500–2500 km during the Devonian period, mostly during early to mid Devonian time (Morris 1976, Ziegler 1978).

The faults bounding the west Norwegian ORS basins relate well, kinematically, to the above, first-order, sinistral mega-shear. On a theoretical basis, the E–W to ENE–WSW fractures can be viewed as second-order, right--lateral, strike-slip or oblique-slip faults (Moody & Hill 1956, Wilcox et al. 1973) splaying and propagating from the first-order structure (Fig. 3). This picture is not quite so simple, however, since the strike-slip motions were themselves secondary or subsidiary to the fundamental, intra-plate, NW–SE to NNW–SSE crustal extension; the overall kinematic regime was thus one of transtension. In this setting the individual basins would have gradually opened by combined, componental, dextral strike-slip (or oblique-slip) and extensile motions (cf. Steel & Gloppen 1980). The dip-slip extensional faults would have tended to splay, or hinge, from the master fault in the manner of listric structures as the pull-apart basin gradually widened, with the migrating depocentre producing successive E–SE onlap of cyclothems across the buried listric splays.

The southern or southeastern basin-margin faults, which are now essentially thrust contacts, were therefore extension fractures during Lower to Middle Devonian time. The subsequent tectonic inversion led to a reversal of the slip vector along these fractures during the Svalbardian contractile phase (Steel et al. 1978). The master extension faults, in some cases, could also have had a listric form judging from observations of regional structure (Bryhni & Skjerlie 1975, Bryhni 1978). This feature would have facilitated their ultimate conversion into sole thrusts, which may have interconnected across the region. Another feature of the transtensional field is that N–S extensional faults may well have developed, under favourable circumstances. The overall slip motion in these ORS basins during their growth would thus be expected to have varied between northwest and west. An interesting exercise would be to attempt to assess the amount of extensional slip involved, i.e. prior to the reversal of motion and initiation of compressional tectonics. In other mountain belts extensional displacements of fault hanging-walls over distances of several kilometres have been recorded (cf. Wernicke 1981).

OTHER DEFORMATION FEATURES

As well as the major, combined dextral-slip and extensile E–W to NE-SW faults arising from the imposed orogen-parallel sinistral mega-shear, NW–SE to NNW–SSE second-order sinistral strike-slip faults of Devonian age are theoretically feasible products of this wrench regime (cf. Moody & Hill 1956). Unlike the dextral fractures, however, these would normally not be expected

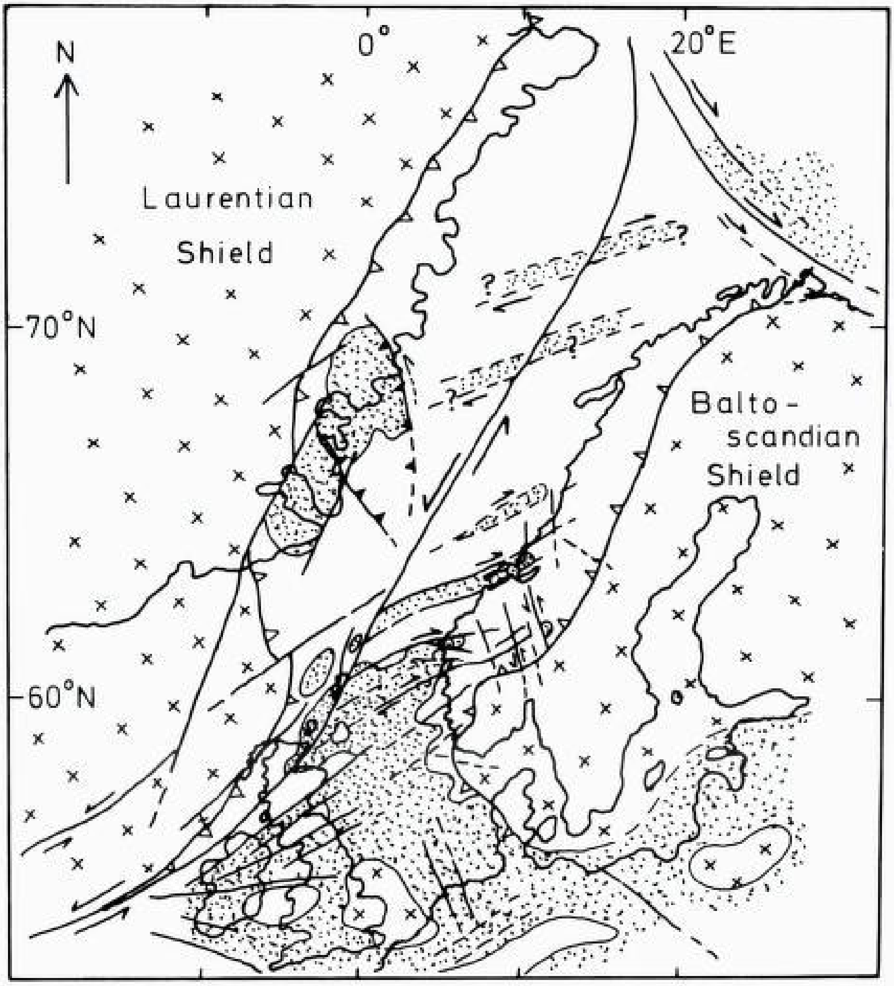

Fig. 3. Simplified map depicting the palaeographic situation and major fractures in the Balto-scandian–Laurentian–British/Irish area in approximately Middle Devonian time: modified from Ziegler (1978, fig. 3).

Ornament: *stippled* – areas of Devonian sedimentation; *crosses* – Precambrian crystalline basement; *white areas* – Caledonian fold belts. Faults are shown by thicker, full lines, with known or deduced strike-slip movement indicated by semi-arrows. Main thrusts are shown by the traditional ticked (triangled) lines. Drillcore data from the North Sea indicate that ORS sediments can be traced from the Scottish basins across to Vestlandet (Ziegler 1978).

to have opened up to produce divergent transtensional basins since they strike sub-parallel to the principal crustal extension trend. Only where fault surfaces were slightly curved, or deflected by pre-existing structures, would such divergence have been possible. Fractures of this trend do occur over large parts of southern Norway, and many carry post-Silurian displacements denoting left-lateral movement (Guezou 1981). However, some of these faults may also have been reactivated during the late Palaeozoic (Hercynian) to early Mesozoic rifting events. The only Devonian pull-apart basin associated with these NW–SE trending faults recorded in Norway is that at Røragen. Others may well have existed, the ORS sediments having since been removed by post-Caledonian erosion.

ORS sedimentation, as noted earlier, was followed by the Svalbardian deformation phase which produced major folds, local very low grade metamorphic fabrics, and inverted the basin-margin dip-slip or oblique-slip dislocations into contractile thrust-faults (Steel et al. 1978). By analogy with the early Devonian complex transtensional regime, this deformation was most likely partly transpressive rather than a simple strike-normal contraction. This is also supported by the fact that although most of the observed thrusts are younger than the fold structures (e.g. Höisæter 1971), there are cases where the thrust surfaces and mylonite zones are also deformed by folds of this same broad generation.

Conclusions

The Old Red Sandstone basinal sediments of southern Norway display a variable deformation by folds, faults, cleavages and thrusts which are part of a late-Caledonian orogenic pulse. Stratigraphic constraints within Norway indicate an Upper Devonian age for these structures; orogen-wide correlations favour a Frasnian age. However, perfect synchroneity of deformation along and across the Caledonian mountain belt is thought to have been unlikely.

Basinal development in Lower to Middle Devonian time (or slightly earlier in the northwest) occurred during the imposition of a fundamental c. NW–SE crustal extension following the major Scandian (Silurian) tectonometamorphic event. This was strongly influenced, however, by a broadly simultaneous orogen-parallel, sinistral strike-slip mega-shear from the Svalbard area south–southwestwards to northern Britain and further into the northern Appalachians. In combination with the fundamental extensile field this produced a transtensional regime with second-order dextral strike-slip faulting acting in unity with the extensional fault motions. Subsequently, in early Upper Devonian time, the transtensional field was replaced by a SE-directed compression, probably in part or even largely transpression. During this contractile stage the NE–SW to E–W trending fold structures were developed, and many of the earlier, syndepositional extension faults (either listric or planar) were rejuvenated as reverse-faults and thrusts. Mylonites were developed along some of the most ductile movement zones, and the ORS rocks and their crystalline substrates were translated east- to southeastwards as thrust sheets over distances of several kilometres and, in some cases, perhaps tens of kilometres (B. A. Sturt pers.comm.). Later movements in some areas produced rather more brittle, NW- to NNE-directed thrusting or reverse faulting, and crenulation cleavages.

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