Extensional tectonics in the North Atlantic Caledonides: a regional view

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Abstract: Extensional structures characterize significant parts of the North Atlantic Caledonides. Silurian extensional deformation took place, particularly in the heated crust in the southern Greenland Caledonides, but the majority of the mapped extensional structures are Devonian (403–380 Ma). They formed by reactivation of low-angle Caledonian thrusts and by the formation of hinterland-dipping shear zones, of which the largest system is located in SW Norway and related to exhumation of the subducted margin of Baltica. The Devonian extension was concentrated to the central and southern part of the Caledonides, with maximum extension occurring in the area between the Western Gneiss Region of SW Norway and the Fjord Region of East Greenland. Kinematic data indicate that the main tectonic transport direction was toward the hinterland, and this pattern suggests that the main Devonian extension/transtension in the southern part of the North Atlantic region was postcontractional while strike-slip motions and possibly transpression occurred farther north. Late Devonian to enigmatic Early Carboniferous ages from UHP metamorphic assemblages in NE Greenland suggest that intracontinental subduction was going on in NE Greenland at a time when extensional deformation governed the rest of the orogenic belt.

The Caledonian orogen as exposed in Norway, Greenland and the northern British Isles (Fig. 1) have traditionally been investigated with an eye for contractional structures. Thrusting as a model for explaining the stratigraphic relations in the Scottish Highlands was already presented in 1858 by James Nicol on his Geological Map of Scotland, although not generally accepted or well documented until the results of Peach and Horne's mapping during the last part of the18th century were published (Peach *et al.* 1907). In the Scandinavian Caledonides the Swedish geologist Alfred E. Törnebohm suggested substantial thrusting of Caledonian units in 1888. It would take several decades before his theory won general acceptance among Scandinavian geologists, but since the early 1900s a large number of geologists have mapped a complex system of thrust and thrust-related structures throughout the Scandinavian, British and Greenland Caledonides.

The recognition of substantial extensional structures at a regional scale in the orogen occurred about a century later, and has been widely accepted in general terms with much less discussion and controversy. Three factors influenced the discovery and understanding of major extensional structures in the Caledonide orogen. One was the eye-opening discovery of low-angle detachments and associated metamorphic core complexes in the Basin and Range Province of the western USA shortly prior to 1980 and onward (e.g. Davis & Coney 1979; Coney 1980; Wernicke 1981), which demonstrated that low-angle faults and mylonite zones should not be regarded as thrusts without critical evaluation. It was however debated whether low-angle faults could form directly (Scott & Lister 1992) or if they rotate from steeper (>30°) dips (Nur *et al.* 1986; Buck 1988). The recognition of low- to unmetamorphosed hanging wall sedimentary rocks above metamorphic gneisses in the Basin and Range core complexes led geologists to look for similar metamorphic breaks across faults and shear zones elsewhere. Such observation were made in SW Norway, where Devonian basins were located above a metamorphic basement with what turned out to include Caledonian eclogites. This way of thinking probably inspired the first published suggestions of an extensional detachment under the Devonian basins of SW Norway, which was in fact made by workers who had never worked in the region (Bjørlykke 1983; Hossack 1984). This extensional structure, now known as the Nordfjord-Sogn Detachment Zone, turned out to be the most profound extensional shear zone in the entire Caledonian orogen.

A second significant discovery was the great improvement in the understanding of kinematic indicators during the 1980s (Berthé *et al.* 1979; Lister & Snoke 1984; Simpson & Schmid 1983), an understanding that also was important for the interpretation and demonstration of the extensional nature of detachments in the Basin and Range. It

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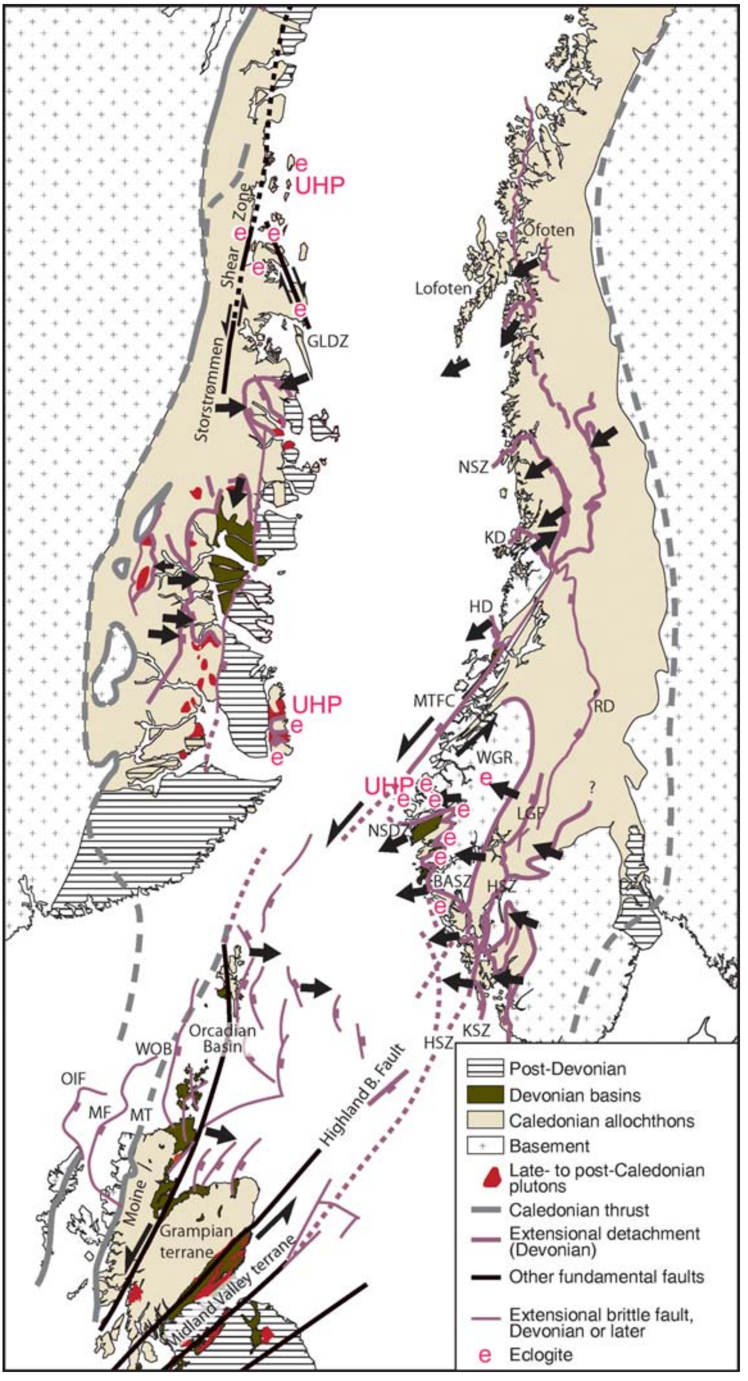

Fig. 1. Geological map of the North Atlantic Caledonides, reconstructed to the situation at the end of the Caledonian orogeny. BASZ, Bergen Arc Shear Zone; HD, Høybakken Detachment; HSZ, Hardangerfjord Shear Zone; KD, Kollstraumen Detachment; LGF, Lærdal-Gjende Fault; GLSZ, Germania Land Deformation Zone; KSZ, Karmøy Shar Zone; MF, Minch Fault; MT, Moine Trust; MTFZ, Møre-Trøndelag Fault Zone; NSDZ, Nordfjord-Sogn Detachment Zone; NSZ, Nesna Shear Zone; OIF, Outer Isles Fault; RD, Røragen Detachment; WGR, Western Gneiss Region; UHP, ultrahigh pressure; WOB, West Orkney Basin.

was the use of kinematic indicators that helped define the substrate to the Devonian basins as a several kilometre-thick extensional shear zone (Norton 1986, 1987; Séranne & Séguret 1987) and to map out the details of this zone (e.g. Andersen *et al.* 1991; Swensson & Andersen 1991; Osmundsen & Andersen 1994; Walsh *et al.* 2007).

The use of kinematic indicators in ductilely deformed rocks was also important for the re-evaluation of the extensive low-angle mylonite zones that had been mapped as Caledonian thrusts, many of which turned out to portray a sense of shear opposite to that predicted by the model of thrust emplacement. Top-to-the-hinterland structures were noted in a few early publications, but had been ascribed to back-thrusting (i.e. contractional deformation) during Caledonian contraction (Banham *et al.* 1979; Milnes & Koestler, 1985), minor extensional movements marking the end of the Caledonian orogeny (Kvale 1960; Naterstad *et al.* 1973) or upper-crustal faulting of Middle Devonian and younger age (Haller 1971). Systematic fieldwork in south Norway revealed that the basal thrust is consistently dominated by top-to-the (N)W structures. Furthermore, a relative age relation was found between this hinterland-directed nappe movement of the Caledonian nappe pile and west to NW-dipping extensional shear zones, and the two sets of structures were referred to as Mode I (backmovement along original thrusts) and Mode II (oblique shear zones, cross-cutting original thrusts) (Fossen 1992; Milnes *et al.* 1997) (Fig. 2).

A third factor that significantly added to the discovery and mapping of extension in the Caledonides was the systematic mapping of metamorphic conditions and application of thermochronologic methods. It was realized that juxtaposition of relatively high-grade footwall lithologies with lower-grade hanging wall rocks characterize major extensional faults and shear zones (Norton 1986). It was also realized that cooling ages and mineral ages provide important constraints on both the timing of extension and the offset across some of the detachments in Greenland and Scandinavia (Lux 1985; Chauvet & Dallmeyer 1992). Most early workers focused on the detachments themselves, which were regarded as extensive, crust-cutting structures. In later years more attention has been devoted to additional distributed coaxial footwall strain to explain the vertical thinning and uplift required to expose (ultra)high pressure rocks in the footwall (Andersen & Jamtveit 1990; Milnes *et al.* 1997; Krabbendam & Wain 1997; Johnston *et al.* 2007*a*).

The discovery of major extensional structures in South Norway was followed by the recognition of extensional shear zones in central and northern Norway (Rykkelid & Andresen 1994; Coker *et al.* 1995; Braathen *et al.* 2000; Osmundsen *et al.* 2003) and in the Greenland Caledonides (Strachan 1994; Hartz & Andresen 1995). In the onshore Scottish Caledonides extensional deformation in the form of ductile shearing seems to be absent, although some brittle reactivation has been described (Holdsworth 1989). In this contribution the different expressions of extensional deformation in the Caledonides will be reviewed and discussed in terms of orogenic and postorogenic evolution.

The Scottish Caledonides

The Scottish Caledonides comprise several tectonic units of largely Neoproterozoic rock complexes that constitute most of the Midland Valley terrane, the Grampian terrane and the Moine and associated nappes. A complex history of Ordovician to Silurian Caledonian deformation and metamorphism is present in this area, with the youngest event in the foreland propagating Moine Thrust Zone. This zone is part of the Scandian orogen that also dominates the Scandinavian and Greenland Caledonides, with the development of the Moine Thrust Zone being early Scandian (*c.* 430 Ma; Holdsworth *et al.* 2007). Extensional detachments of the magnitude and number found in the Norwegian and Greenland parts of the Caledonian orogen are not present. Extension-related features in Scotland are mostly minor structures within the orogenic wedge onshore NW Scotland, the deposition and early deformation of the Orcadian basin, Devonian deformation structures found in Shetland and strike-slip or transtensional structures of southern Scotland (Fig. 3).

Extensional structures within the onshore Moine Thrust system are rare (see below). Holdsworth (1989) identified two sets of subsidiary extensional structures in the Moine Thrust wedge; an early set of low-angle faults and associated folds formed by extensional reactivation of the Caledonian mylonitic fabric, and steeper secondary extensional faults, all of which were thought to predate the formation of the Devonian West Orkney Basin (Holdsworth 1989). Whether these structures are related to the profound Devonian extensional collapse of the Caledonian orogen seen in Scandinavia and Greenland is unclear. Coward (1982, 1983) interpreted late low-angle extensional faults in the Moine Thrust zone as surge structures related to a collapsing frontal part of the thrust complex due to gravitational instabilities in the orogenic wedge. Another extensional structure, the Sound of Iona Fault, was considered to be a ductile extensional structure with several kilometres of throw, but was predated by the 414 ± 3 Ma Ross of Mull Granite

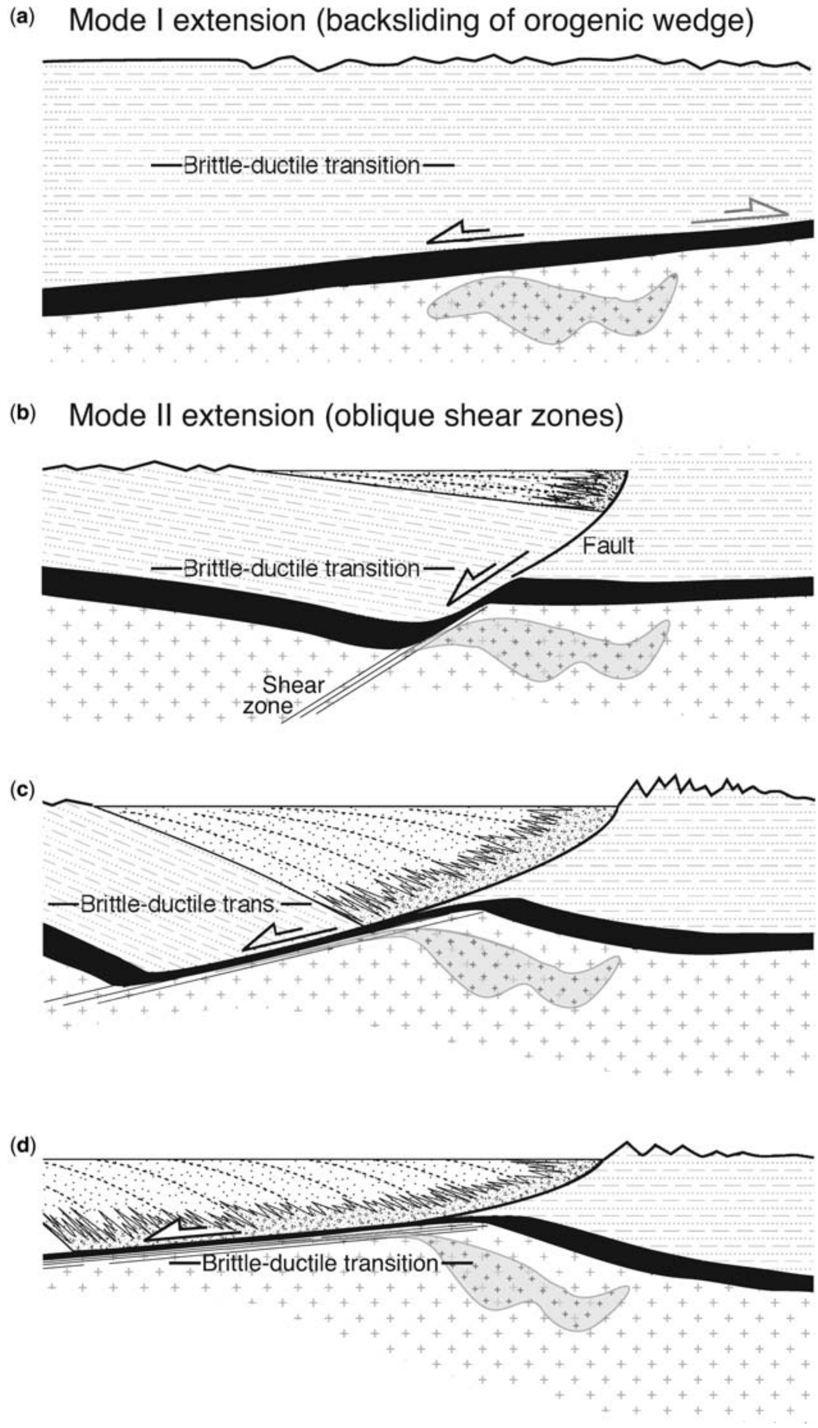

Fig. 2. Illustration of the two modes of extensional detachment formation in the Caledonides. Mode I (**a**) is reactivation of thrusts as extensional detachments, while Mode II detachments form by the initiation of dipping faults (**b**) that rotate to lower angles with increasing strain. The latter type can develop hanging wall basins with rotating beds that can build up to very thick stratigraphic sequences (**c–d**).

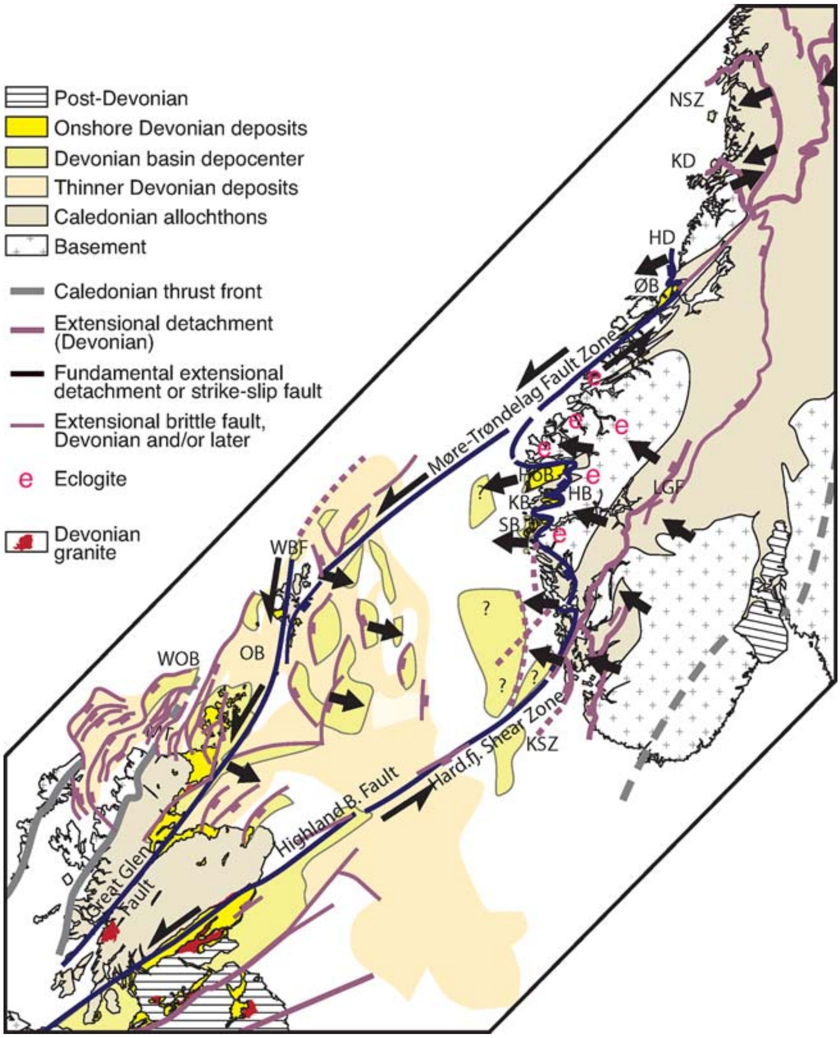

Fig. 3. Illustration of the strike-slip overstep model for the Devonian extensional system between southern Norway and northern Britain. Black faults indicate the main faults in this system, and arrows indicate kinematics. OB, Orcadian basin. See Figure 1 for other explanations.

(Potts *et al.* 1995) and therefore also syncontractional, at least in a large-scale context.

Onshore Scotland and on Orkney Devonian deposits are found to rest unconformably on the pre-Devonian substrate, and affected by minor faults only. However, deep seismic traverses across the offshore extension of the Moine and related Caledonian thrusts into the West Orkney Basin (Brewer & Smythe 1984) reveal more substantial extensional reactivation of Caledonian thrusts in this area (Enfield & Coward 1987; Snyder 1990). Late Lower (Pragian to Emsian; Marshall & Hewett 2003) to Middle Devonian (398–385 Ma) sediments fill extensional half-grabens above the reactivated thrusts, suggesting that Caledonian thrusts acted as brittle basin-bounding extensional faults during Middle Devonian NW–SE extension (Coward *et al.* 1989). Coward *et al.* (1989) estimated the horizontal Devonian extension across the West Orkney Basin to a few tens of kilometres, decreasing to the SW.

The Devonian strata are gently folded and faulted in the Orkney Isles, but deformation is more pronounced in the Devonian rocks of Shetland. The deformation is most intense along the steep faults that transect this region. In particular, the Walls

Boundary Fault, which appears to connect with the Great Glen Fault farther south (Fig. 1), is thought to have played a significant role during the Devonian deformation of the Shetland area. Middle(?) Devonian inversion along these basement-rooted faults has been linked to sinistral strike-slip fault movements (Coward *et al.* 1989; Watts *et al.* 2007), possibly related to Devonian sinistral slip on the Highland Boundary Fault to the south.

Sinistral slip has also been found on the NW–SE striking Devonian shear zone along the Møre-Trøndelag Fault Zone in western Norway (Fig. 3) (Séranne *et al.* 1991). This shear zone is connected to a major system of Middle Devonian basins and extensional detachments and shear zones along the SW coast of Norway, and it seems likely that there was a connection between the extension-related developments on the two sides of the northern North Sea. Séranne *et al.* (1991) and Séranne (1992*a*) suggested that the basins and structures all fit into a large-scale transtensional overstep in a sinistral system of faulting dominated by NE–SW-trending faults. In this model, extension occurs in a large-scale pull-apart structure between the Møre-Trøndelag Fault Zone and similarly orientated faults farther south, primarily the Highland Boundary Fault and perhaps also the Southern Uplands Fault (Fig. 3). All of these faults show evidence of sinistral shear in the Devonian. Early Devonian transtension in the Midland Valley area has been favoured (Bluck 1984; Smith 1995; Soper & Woodcock 2003) while the Mid-Devonian situation in the UK is less clear. Dewey & Strachan (2003) suggest that transtension prevails into the Middle Devonian, while Soper & Woodcock (2003) prefer a model where the Acadian orogeny causes a change from transtension to transpression (see also Mendum & Noble 2010). The Highland Boundary Fault (or its Caledonian precursor) links with the Hardangerfjord Shear Zone, as seen on magnetic and gravitaty maps as well as later fault trends along the projected line of extension across the North Sea (Fossen & Hurich 2005). However, the onshore part of the Hardangerfjord Shear Zone appears to have acted as a normal (dip-slip) shear zone at this time (Fossen & Hurich 2005), hence the NE margin of such a pull-apart basin must be defined by the coast-parallel extensional shear zones along SW Norway (Nordfjord-Sogn Detachment Zone, Bergen Arcs Shear Zone), as shown in Figure 3.

The Greenland Caledonides

General setting

The 1300 km long Caledonian orogen in East Greenland has long been considered the counterpart to the Scandinavian Caledonides and a northward continuation of the Scottish Caledonides (e.g. Haller 1971; Higgins & Phillips, 1979). The Greenland and Scandinavian Caledonides also share many of the same features, although with some important differences (Fig. 4). Both orogenic belts are of comparable width and length (Fig. 1), and a Scandian (Silurian to Early Devonian) orogenic wedge have been thrust above a Precambrian basement and its sedimentary cover of Neoproterozoic to Ordovician age. The Greenland orogenic wedge contains nappes of Precambrian continental basement as well as its sedimentary cover (Higgins *et al.* 2004), similar to the Moine Nappe and several Scandinavian nappes, and displacements of 200–400 km have been estimated for the highest allochthonous units (Higgins & Leslie 2000).

Oceanic nappes derived from Iapetus have not been found, but Caledonian S-type granitoids (435–425 Ma) are widespread in the East Greenland Caledonides. This is in contrast to their Scandinavian counterpart where ophiolite complexes are widespread and granitoids are almost exclusively arc-related. No sign of early Caledonian (pre-Scandian) orogenic activity is found in Greenland, where continental deposition occurred continuously from the Cambrian to the Middle Ordovician (southern and central part) and to the late Llandovery (*c.* 430 Ma, northern part), when the Laurentian margin was overthrust by Caledonian nappes. The general thrusting direction in the Greenland Caledonides is to the west or WNW, that is, at a high angle to the Caledonian collision zone and opposite the Caledonian thrusting direction in Scandinavia. In addition there are orogen-parallel strike-slip shear zones and faults of somewhat unclear significance, particularly in the NE Greenland Caledonides (Larsen & Bengaard 1991; Strachan *et al.* 1992). Strike slip zones are also important structures in the Svalbard and British Caledonides south of the Moine Thrust System, and all of these regions have been viewed in terms of strain-partitioned transpression (Strachan *et al.* 1992), with a switch from orthogonal shortening to sinistral transpression around 430 Ma in the Scottish Caledonides (Dewey & Strachan 2003). Others relate strike-slip movements in the Greenland Caledonides to a late- to post-collisional Devonian transtensional setting, as portrayed in Fig. 3 for the North Sea area (Larsen & Bengaard 1991).

Structural framework

The lowermost Caledonian tectonic units contain parautochtonohous foreland deposits of Proterozoic to Ordovician age, exposed in the western tectonic windows. South of 76°N (Fig. 5) these low-grade units are overthrust by Caledonian allochthons that

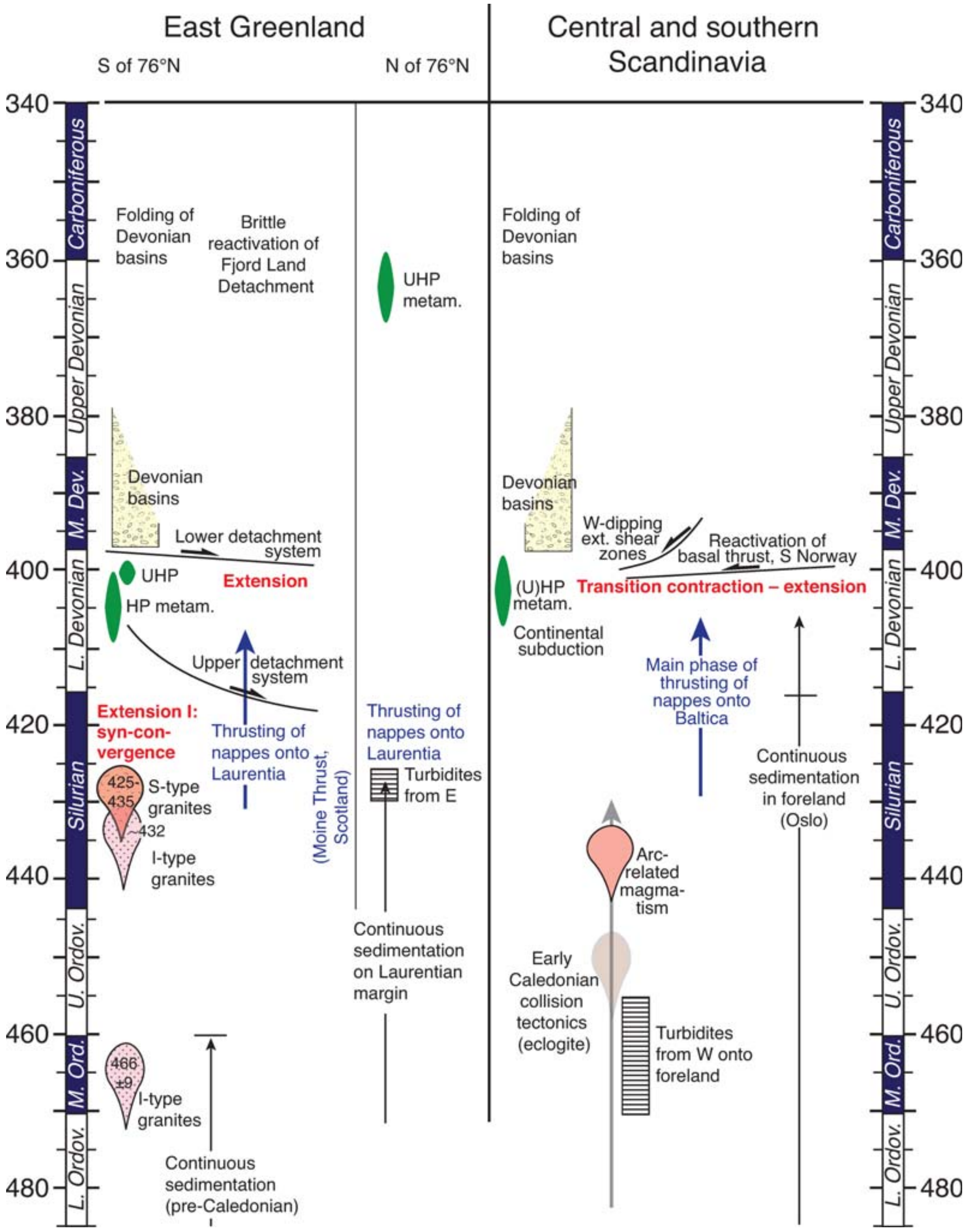

Fig. 4. Timing of orogenic activity in the Caledonides of the North Atlantic region.

have also been affected by later extensional detachment faulting. Different views exist on the Caledonian tectonistratigraphy of this part of Greenland, partly stemming from different views on the role of extensional versus contractional deformation. In particular, the subdivision generally used by the Geological Survey of Denmark and Greenland (GEUS) and associated workers (e.g. Higgins *et al.* 2004), where three major thrust sheets are defined (Niggli Spids thrust sheet, Hagar Bjerg

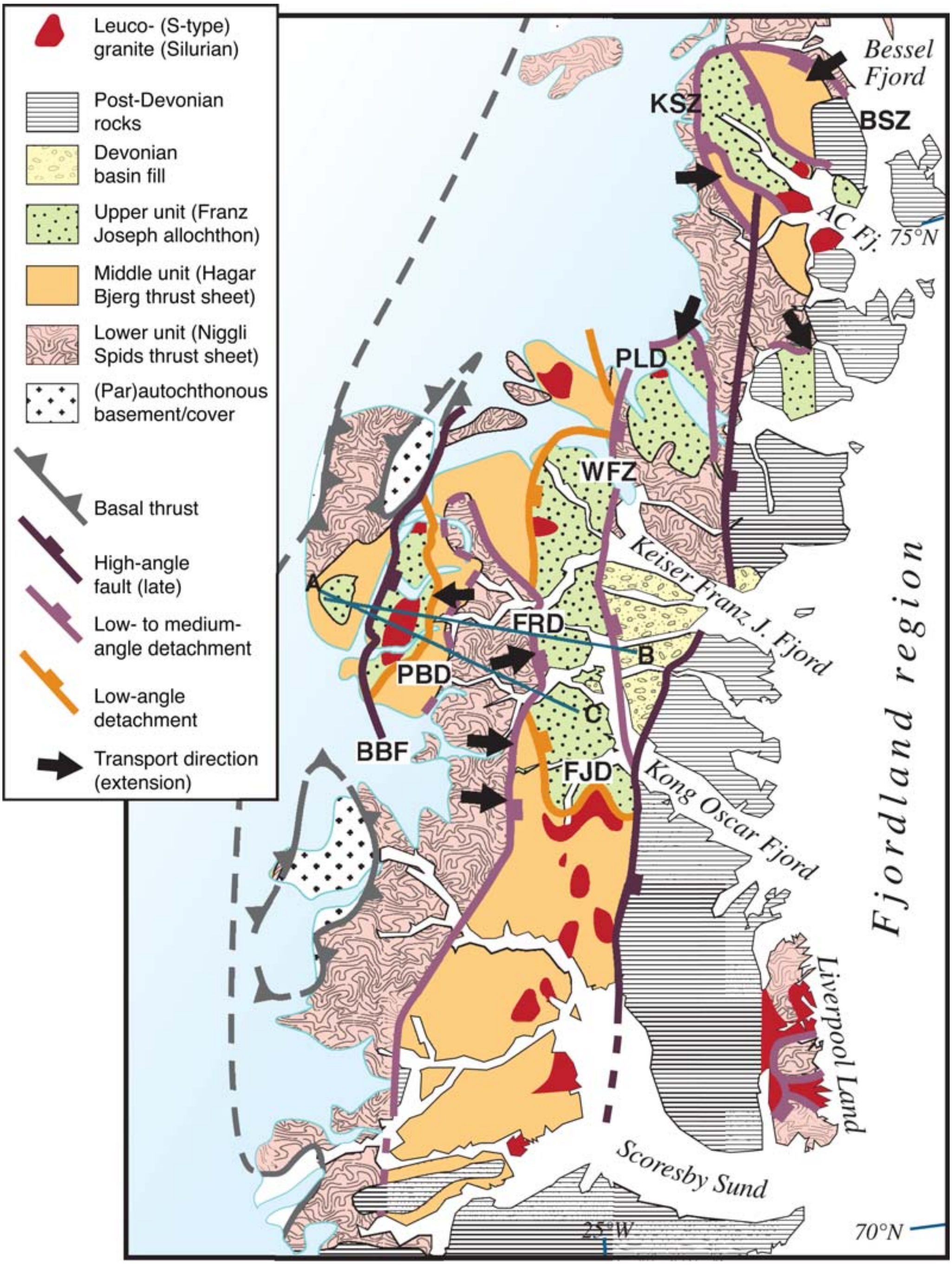

Fig. 5. The Greenland Caledonides between 76° and 70° N. Based on Higgins *et al.* (2004), Andresen *et al.* (2007) and Gilotti & McClelland (2008). AC, Ardencaple Fjord; BBF, Boyd Bastionen Fault; BSZ, Bessel Fjord Shear Zone; FRD, Fjord Region Detachment; FJD, Franz Joseph Detachment; KSZ, Kildedal Shear Zone; PBD, Petermann Bjerg Detachment; PLD, Payer Land Detachment; WFZ, Western Fault Zone.

thrust sheet and Franz Joseph allochthon), was challenged by Andresen *et al.* (2007), who regarded these units as a single nappe, disrupted by extensional detachments only. Although most workers now agree that extensional deformation plays an important role in the shaping of the present Greenland Caledonides, there is considerable disagreement about the relative role of thrusting versus extension. At present it may be useful to broadly maintain the tectonostratigraphy of Higgins *et al.* (2004) for the central and southern parts of the Greenland Caledonides, but by referring to the different units as three allochthons units rather than nappes (Fig. 6), as suggested by Gilotti & McClelland (2008), with the origin of shear zones and detachments being kept open.

The lower allochthonous unit (Niggli Spids thrust sheet of Higgins *et al.* 2004) consists of Archaean to Palaeoproterozoic amphibolite-facies gneisses and a several kilometre-thick sequence of Meso- to Lower Neoproterozoic metasedimentary rocks (Krummedal sequence) that have been deformed and metamorphosed in the Precambrian as well as during the Caledonian orogeny. Relics of high-pressure eclogite and granulite-facies Caledonian metamorphism have recently been reported from this unit, overprinted by amphibolite-facies metamorphism (Gilotti *et al.* 2008). While the general view is that these rocks experienced a history of Caledonian thrusting, an alternative model calls for extensional flow at mid- to lower-crustal levels to explain the amphibolite-facies metamorphism (Andresen *et al.* 1998).

Gneisses of the Liverpool Land peninsula are traditionally considered to belong to this unit, and the occurrence of ultrahigh-pressure metamorphism in this area deserves special attention. Eclogites record pressures in excess of 2.5 GPa and temperatures of *c.* 800 °C, and the age of metamorphism is interpreted as *c.* 400 Ma based on zircon U–Pb dating (Hartz *et al.* 2005). It has recently been suggested that the Liverpool Land eclogite terrane

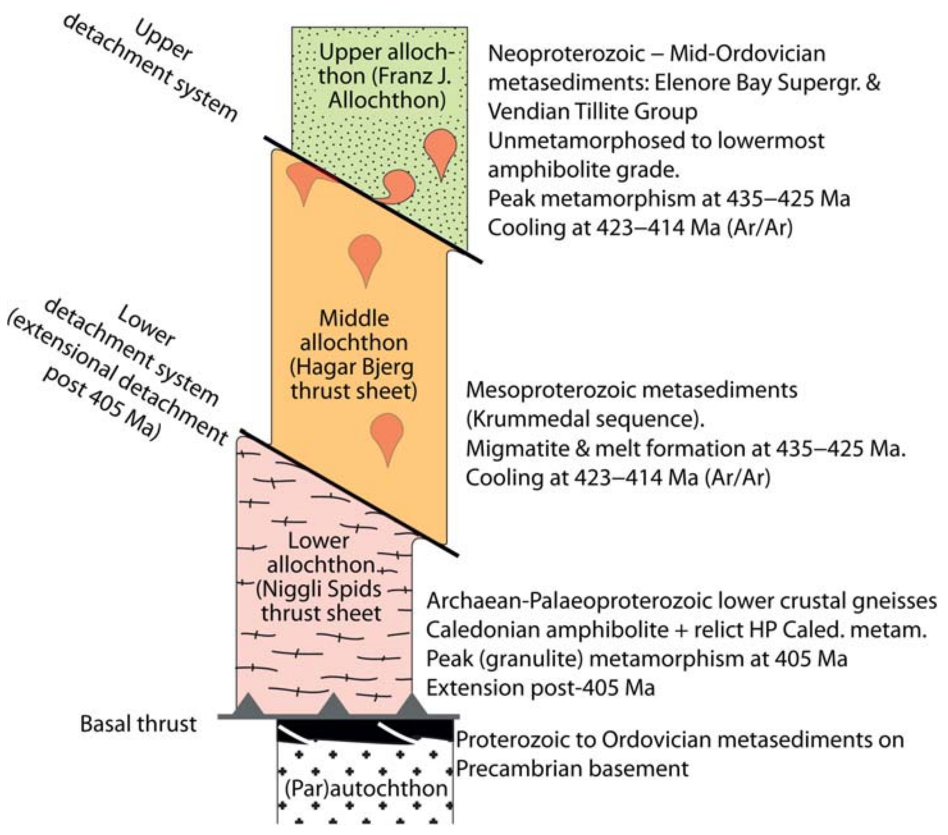

Fig. 6. Tectonostratigraphy of the Greenland Caledonides of the Fjordland Region. Two detachment systems occur within the orogenic wedge, referred to as the upper and lower system by Gilotti & McClelland (2008). Note that the upper detachment system locally cross-cuts the lower one.

is a fragment of Baltica (Western Gneiss Region) based on the similar eclogite ages and occurrence of peridotite in both areas (Augland *et al.* 2009).

The middle allochthonous unit (Hagar Bjerg thrust sheet) is also dominated by Mesoproterozoic metasedimentary rocks of the Krummedal sequence, together with subordinate orthogneiss, that is, similar to the lower allochthon (Niggli Spids thrust sheet). The main difference between the two units is the extensive migmatitization of the Krummedal sequence and the presence of two families of very similar-looking S-type granites in the middle allochthon. The older granites appear to be related to Proterozoic migmatitization of the Krummedal metasediments, while the younger ones are Caledonian (435–425 Ma) (Kalsbeek *et al.* 2001, 2008) and connected to a Silurian phase of partial melting.

The upper allochthonous unit (Franz Joseph allochthon) consists of generally low-grade to unmetamorphosed Neoproterozoic to Mid-Ordovician sediments deposited on the Laurentia margin. The Neoproterozoic to Ordovician Elenore Bay Supergroup and the Vendian Tillite Group dominate this unit, which is considered to have been carried passively on the substrate (middle unit) before the formation of extensional detachments (Higgins *et al.* 2004). It is possible that the separation of the middle and upper allochthonous units is caused by extensional shearing (Andresen *et al.* 2007), which would make the upper allochthonous unit extensional by origin.

In the northern part of the East Greenland Caledonides, the undeformed foreland sequence of Neoproterozoic to Silurian strata are well represented and flanked to the east (Kronprins Christian Land) by a thin-skinned fold-and-thrust belt where mostly Ordovician–Silurian rocks are involved (e.g. Higgins & Leslie 2008). The foreland deposits are overridden by a thrust sheet of Neoproterozoic rocks (the Vandredalen thrust sheet), and farther east by thrust sheets containing basement gneisses. Orogen-parallel transport has been reported from these units and explained in terms of oblique collision (transpression) between Baltica and Laurentia (Holdsworth & Strachan 1991; Strachan *et al.* 1992) or Devonian transtension (Larsen & Bengaard 1991). Age determinations suggest that the two main strike-slip shear zones, the sinistral Storstrømmen and the dextral Germania Land deformation zone (Fig. 1), initiated in Middle(?) Devonian times (Gilotti *et al.* 2008) and therefore are of late- or post-Caledonian significance. As seen in the southern part of the Greenland Caledonides, thrust sheets derived from the Laurentia margin show a progressive increase in age and metamorphic grade from west to east (Higgins *et al.* 2001). In NE Greenland the highest pressures are recorded in eclogite enclaves in the eastern parts of the exposed nappe stack (Nørreland thrust sheet) (Fig. 1).

Devonian (ultra)-high pressure metamorphism

Evidence of high-pressure (HP) metamorphism is found in both the southern and northern part of the East Greenland Caledonides and several age determinations from both parts indicate an Early Devonian age for the eclogitization (*c.* 410–390 Ma) (Gilotti *et al.* 2004; Gilotti & McClelland 2007). In the northern part of the orogen, local ultra-high pressure (UHP) metamorphism has, quite surprisingly, been dated to be significantly younger at 365–350 Ma (Gilotti *et al.* 2004; Lang & Gilotti 2007). Based on these SHRIMP ^{206}PB/^{238}U ages Gilotti *et al.* (2004) suggested that the collisional (Scandian) phase be extended through the Devonian and into the lowermost Carboniferous. Such anomalously young ages seriously challenge existing models for the Caledonian evolution and termination. They also imply considerable exhumation and extension to have taken place after 365–350 Ma in order to expose ultrahigh-pressure rocks that formed at 970 °C and 3.6 GPa (Lang & Gilotti 2007). If these ages are reliable and correctly interpreted, the history of Caledonian-related extension in Greenland may have been a very long one, and existing models for the Caledonides need substantial modification, as discussed later on.

The Devonian basin

More than 8 km of Middle (Eifelian) and Late Devonian coarse continental clastic sedimentary rocks occur in what is regarded as remnants of a single Old Red sedimentary basin in the south-central part of the Greenland Caledonides (Larsen *et al.* 2008). The sedimentary rocks unconformably overlie Cambro-Ordovician and locally older rocks in the north and locally in the west. However, the Western fault zone runs along the present western margin of the Devonian basin, separating it from late Proterozoic sediments of the Eleonore Bay Group. In the east the basin fill is in fault contact with Lower Palaeozoic and post-Devonian rocks (Fig. 5).

Similar to other Devonian basins in the North Atlantic region, the basin formation is linked to the extensional collapse of the Caledonides (McClay *et al.* 1986), although an influence of sinistral strike slip faulting has been suggested (Larsen & Bengaard 1991). Andresen & Hartz (1998) disregarded Devonian strike-slip in this context, and linked the basin to a major extensional detachment to the west (the Fjord Region Detachment; Fig. 7a) and considered the West fault zone that

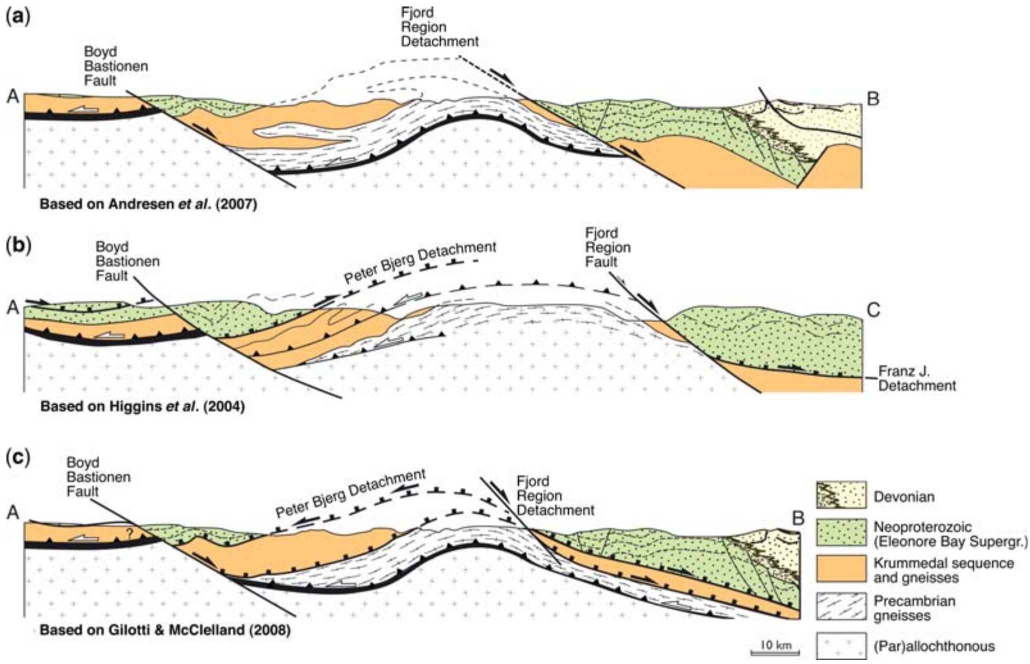

Fig. 7. Profiles across the East Greenland Caledonides in the Fjordland Region (see Fig. 3 for location), reflecting three different interpretations. (**a**) Andresen *et al.* interpret the detachments as basement faults; (**b**) Higgins *et al.* (2004) distinguish between subhorizontal detachments along Caledonian thrusts and basement-transecting detachments; and (**c**) Gilotti & McClelland (2008) interpret most of the detachments as intra-wedge detachments (the Boyd Bastionen is interpreted as a late fault).

runs along the west margin of the basin as a subsidiary hanging wall normal fault. This model implies that the Devonian basin (half graben) extended some 50 km west of its present location.

Extensional detachments and faults

Although the presence of extensional faults in the East Greenland Caledonides has been recognized for a considerable amount of time (Fränkl 1953; Haller 1971), their abundance and profound influence on the Caledonian orogenic wedge has become increasingly clear since the early 1990s. In a sense, the thinking has gone from pure contraction to extension via strike-slip faulting, which was suggested as a key element in the formation of the Devonian basin (Larsen & Bengaard 1991) and which is still considered to be and important element in the Caledonides north of 76° (Strachan *et al.* 1992; Smith *et al.* 2007). At present, a number of extensional structures have been mapped, particularly south of 76° N, although more work is needed to fully understand their extent, interconnection, temporal development and regional significance. This becomes obvious when comparing the different views on the role of extensional deformation in this part of the Caledonides, which range from a fairly limited modification of the Caledonian contractional thrust architecture (Higgins *et al.* 2004) to models where extensional detachments completely control the present map pattern of the East Greenland Caledonides (Gilotti & McClelland 2008) and where the classical tectonostratigraphy outlined in Higgins *et al.* (2004) and several earlier views are challenged (Andresen *et al.* 2007).

Documented extensional shear zones and faults are developed and studied in the central and southern part of the Greenland Caledonides (south of Bessel Fjord), and many of them show similar characteristics. Several extensional shear zones in the northern part of Fig. 5 near Ardencaple Fjord were described by Strachan (1994), juxtaposing different levels of the tectonostratigraphy, locally with a late brittle development (Gilotti & McClelland 2008). The shear zones in this area show more or less east–west extension.

The largest in terms of length is the west-dipping *Fjord Region Detachment* (Andresen *et al.* 1998) and its extension to the south (Figs 5 & 7). This low-angle detachment is an up to 1 km-thick mylonite zone that originated at more than 25 km depth, possibly considerably more (30 km of crustal omission is estimated by Gilotti & McClelland 2008) and developed during progressively lower P–T conditions. At higher crustal levels strain localized to a 10–50 m thick brittle fault within the shear zone, and the fault is seen in the field to be slightly steeper than the mylonite zone (Andresen *et al.* 1998). The Fjord Region Detachment, which extends along strike for several hundred kilometres, brings the sedimentary rocks of the upper allochthohous unit in fault contact with Precambrian gneisses that may belong to the lower (Gilotti & McClelland 2008) or middle (Andresen *et al.* 2007) units and cuts across contractional fold structures in the hanging wall. A metamorphic break between the greenschist-facies hanging wall metasediments and the amphibolite-facies mylonites of the shear zone is characteristic and supports the impression that the extensional down-to-the-east displacement amounts to several tens of kilometres.

The *Payer Land detachment* (Gilotti & McClelland 2005) juxtaposed HP/HT granulites with metasediments of the greenschist-facies upper unit (Eleonore Bay Supergroup). This is the largest metamorphic break mapped across an extensional detachment in the Greenland Caledonides and the displacement is estimated to 80–100 km (throw of 40–50 km) (Gilotti & MacClelland 2008).

Extensional detachments that have received less attention are the Petermann Bjerg Detachment and the Boyd Bastionen Fault. The former consists of several low-angle and west-dipping shear zones with a top-to-the-NNW sense of shear. The Boyd Bastionen Fault, however, is a steeper, east-dipping brittle fault with down-to-the-east offset that postdates the shear on the Petermann Bjerg Detachment (Gilotti & McClelland 2008).

Detachment geometry

The Fjord Region Detachment and several other extensional shear zones downthrow to the east, typically with low to intermediate dips. The behaviour of these ductile detachments at depth has not received much attention, and conflicting interpretations seem to exist, as shown in Figure 7. Andresen *et al.* (1998, 2007) present the Fjord Region Detachment as a shear zone that truncates the basal thrust and extends into the underlying basement, similar to the Mode II shear zones in the Scandinavian Caledonides (Fossen 1992). Hartz *et al.* (2001) on the other hand seem to let this and similar detachments flatten out at the basal thrust level. Higgins *et al.* (2004) distinguished between very low-angle detachments formed by reactivation of Caledonian thrusts (e.g. Peter Bjerg Detachment in Fig. 7b) and somewhat younger and steeper basement-rooted faults (Boyd Bastionen Fault and Fjord Region Fault), again similar to the Mode I–II extensional development in Scandinavia. Gilotti & McClelland (2008) maximize the concept of very low-angle detachments to the point where they form a more or less continuous and interconnected detachment framework. They sorted the detachments into a lower and an upper system that separate the lower, middle and upper allochthonous units (Fig. 6). These detachments, which themselves do not extend into the autochthonous basement according to Gilotti & McClelland (2008), were then transected by brittle faults at a relatively late (post-Devonian) stage.

Timing of extensional deformation in Greenland

It has proven challenging to constrain the extensional deformation events both in absolute time and relative to the contractional deformation within the East Greenland Caledonian belt. Reference is often made to Caledonian leucogranites, which yield ages around 435–425 Ma according to Hartz *et al.* (2000, 2001); Watt *et al.* (2000); Kalsbeek *et al.* (2001); White & Hodges (2002) and Andresen *et al.* (2007). Emplacement of these granites was partly pre- and partly (mostly) syntectonic according to the same authors. Some of these granites are reported to be syn-thrusting (Higgins *et al.* 2004), with ages around 429–422 Ma (Hartz *et al.* 2001; White & Hodges 2002; Andresen *et al.* 2007), while others are reported to be involved in extensional detachment faulting (Hartz *et al.* 2000; Strachan *et al.* 2001; White & Hodges 2002; Andresen *et al.* 2007), formed by decompressional melting and migmatization (Hartz *et al.* 2001; Kalsbeek 2001). The extension-related dates (430–424 Ma; Strachan *et al.* 2001; White & Hodges 2002; Andresen *et al.* 2007) largely overlap with the thrusting-related ones, i.e. synchronous contraction and extension around 425 Ma. Furthermore, based on age determinations of migmatites and granites intruded at different crustal levels, Andresen *et al.* (2007) presented a model where contractional deformation occurred in the middle crust while the upper crust extended around 429–425 Ma, while Gilotti & McClelland (2008) favour a slightly younger age for the high-level extension (420 Ma). $^{40}Ar/^{39}Ar$ thermochronological data reported by White & Hodges (2002) suggest a phase of extension around 425 Ma and a Devonian one (*c.* 414–380 Ma) that affected deep structural levels. All together, the data indicate syn-convergent Silurian extension within the Caledonian orogenic wedge, a situation reminiscent of that seen in the present-day Himalayan orogen (e.g. Burchfiel *et al.* 1992), and Devonian extension and exhumation that appear to be post-Scandian (e.g. White & Hodges 2002).

As for the deep parts of the crust, Gilotti & McClelland (2005) suggest that the extensional faulting responsible for exhumation of deep-level rocks in the orogen mainly occurred (shortly) after *c*. 405 Ma, the U–Pb age they present for high-pressure granulite-facies metamorphism in the lower unit. A number of $^{40}Ar/^{39}Ar$ cooling ages fall around 400 Ma (White & Hodges 2002) or slightly younger (Dallmeyer *et al.* 1994), and an $^{40}Ar/^{39}Ar$ date of pseudotachylyte in the brittle deformation on the Fjord Region Detachment reveals that this detachment had reached upper crustal levels as the Devonian basin formed. This pattern of Devonian extension fits the timing of extensional detachments in the Scandinavian Caledonides, as discussed later.

The Scandinavian Caledonides

The *c*. 1800 km long belt of Caledonian deformation and metamorphism in Scandinavia is, in simple terms, built upon a Precambrian basement (Baltica) and its Neoproterozoic to Ordovician cover that becomes increasingly involved in Caledonian deformation and metamorphism toward the west coast. Remnants of an orogenic wedge consisting of thrust nappes derived from the Baltica margin as well as the Iapetus ocean (e.g. Gee *et al.* 2008) rest on this basement. These nappes have been translated up to hundreds of kilometres from the collision zone towards the foreland, with a general increase in translation from the short-transported lower nappes to the highest nappe units. A nappe stratigraphy has been assigned to the allochthonous units, which range from the relatively short-transported derivatives of the precollisional Baltica continental margin (Lower and Middle Allochthon) via outboard nappes derived from the Iapetus ocean (Upper Allochthon) to far-travelled units of possible Laurentian affinity (Uppermost Allochthon) (Gee *et al.* 1985; Roberts 2003).

The accumulation of Caledonian allochthons in a more than 1800 km long and 500 km wide orogenic wedge caused severe deformation and metamorphism of the units involved. Hence, many nappes are pervasively deformed although the interior of some large crystalline nappes, such as the Jotun Nappe of southern Norway, are only gently affected by Caledonian deformation and metamorphism.

The magmatic and metamorphic pattern is different from that of the Greenland Caledonides, with less evidence of synorogenic partial melting (migmatitization) or granite emplacement in nappes derived from the Baltica margin, but with abundant greenschist to amphibolite-facies magmatic arc-related complexes. Also, (ultra)high-pressure rocks appear to be more widespread than in the Greenland Caledonides, particularly in the major southwestern basement window known as the Western Gneiss Region (Figs 1 & 8) (Krogh 1977; Wain 1997; Carswell & Cuthbert 2003). This general pattern suggests a cooler crust that locally experienced very high pressures. Coupled with the fact that Caledonian pressure estimates increase dramatically toward the collision zone (hinterland), this has led to the generally accepted model of west-directed subduction of oceanic crust and eventually the Baltica margin (Krogh 1977) under Laurentia during the Silurian-Early Devonian Scandian orogeny (Griffin *et al.* 1985; Andersen *et al.* 1991). Exhumation of the (ultra)high-pressure rocks and the western part of the Scandinavian Caledonides in general is explained in terms of Devonian extensional deformation (e.g. Norton 1986; Andersen & Jamtveit 1990; Andersen *et al.* 1991; Johnston *et al.* 2007*a*, *b*) and commonly linked to the formation of Devonian basins (Norton 1987; Andersen & Osmundsen 1994).

Extensional deformation structures that can be related to the Caledonian orogen have been found from the southwesternmost part (Stavanger area) to northern Norway (Rombak window) (Fig. 1). The majority of these structures are Early to Middle Devonian in age and postdate the construction of the Scandinavian Caledonides. They were first mapped in SW Norway, which is also the area where they are best developed, most studied and best understood.

Extensional back-sliding of the orogenic wedge in south Norway

The Caledonian orogenic wedge rests on a weak basal décollement zone of mostly metapelites (slates, phyllites and micaschists) (Fig. 8) that acted as the Caledonian sole thrust on which allochthonous units were transported to the east and SE (e.g. Hossack & Cooper 1986). However, regional kinematic mapping of the well exposed basal décollement zone in South Norway has shown that the top-to-the-east and SE structures were consistently overprinted by asymmetric folds, cleavage and mylonitic kinematic structures indicating transport to the west and NW (Fossen 1992). The overprint can be traced east of the Jotun Nappe, east of the area covered by Figure 8 and well into the thin-skinned part of the orogen. The intensity of this deformation is remarkable, but nevertheless largely overlooked even in very detailed structural reports (e.g. Kvale 1948).

However, some did report (N)W-vergent structures, such as Banham *et al.* (1979) who interpreted them as contractional, having formed on the Laurentian side of a Caledonian suture. Others regarded

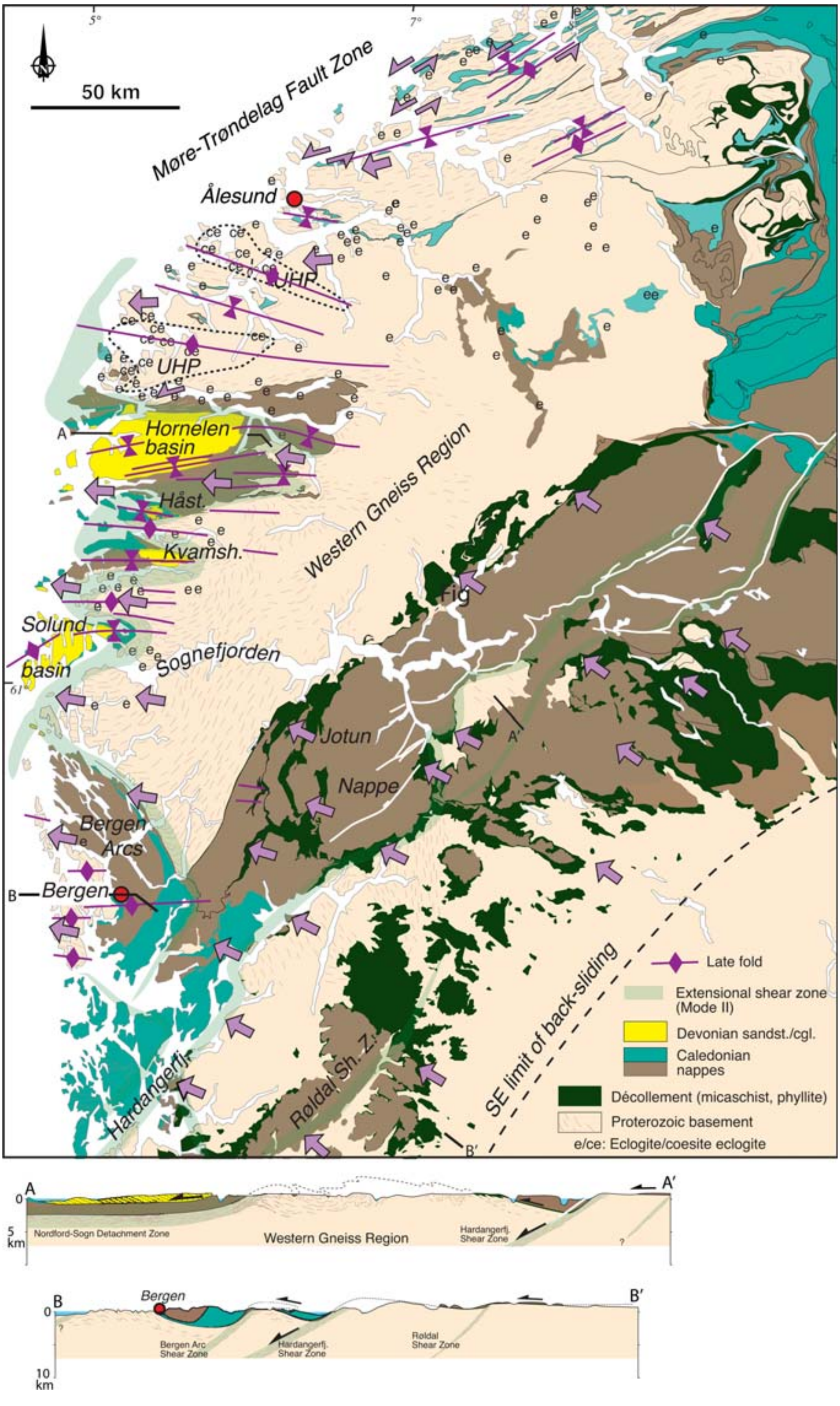

Fig. 8. Geological map of SW Norway showing the locations of Devonian basins, dipping extensional shear zones and high-pressure (eclogite) and ultrahigh-pressure (coesite eclogite) parageneses. Eclogite locations from Young *et al.* (2007).

top-to-the-NW structures as an expression of some sort of back-thrusting (Milnes & Koestler 1985), implying a synorogenic, contractional origin. Naterstad *et al.* (1973) noted the SE-dipping cleavage of the décollement zone and late NW-verging folds and described them as 'puzzling, unsatisfactorily explained features that perhaps indicate a late northwestward movement of the allochthonous cover rocks relative to the basement'.

As the picture of a general northwestward increase in pressure and temperature of the late Caledonian metamorphic mineral assemblages was further elucidated from the 1980s onwards (Fossen 2000 and references therein), it became clear that the basal décollement zone was dipping to the NW at the end of the Caledonian orogeny (Hossack & Cooper 1986). With this geometry in mind it became obvious that the kinematic reversal on the basal décollement (Fig. 2a) is not related to back-thrusting or other contractional deformation, but implies crustal extension on a regional, if not orogenic scale (Fossen 1992). The reversal of shear sense on the décollement zone can be traced up to 300 km east of the present SW Norway coast line, well east of the major Caledonian nappes containing detached Baltic crust, such as the Jotun Nappe (Fig. 8). The back-sliding of the orogenic wedge in South Norway, referred to as Mode I extension in some works (Fossen 1992; Milnes *et al.* 1997) has been roughly estimated to 20–36 km (Fossen & Holst 1995) and dated to approximately 400 Ma (Fossen & Dallmeyer 1998; Fossen & Dunlap 1998).

West- and NW-dipping extensional shear zones

In addition to the back-sliding of the orogenic wedge by reactivation of Caledonian thrusts, a number of (originally) steeper extensional shear zones transect the Caledonian nappe stratigraphy and extend into the basement (Mode II extension of Fossen 1992, see Fig. 2b). One of these is the *Hardangerfjord Shear Zone*, a several hundred kilometres long NW-dipping basement shear zone that affects the overlying nappes by forced folding and faulting (Fig. 8, profiles). Offshore seismic sections across this shear zone show that this is a basement shear zone extending into the lower crust (Fossen & Hurich 2005). Furthermore, there is a marked back-rotation of the Caledonian nappes and the basal décollement across the Hardangerfjord Shear Zone, along with a change from thin- to thick-skinned Caledonian tectonics.

Several other basement shear zones occur, some dipping to the NW and others with a more westerly dip and remarkably curved map pattern. Interestingly, they all involve hanging wall translations toward the hinterland. Coast-parallel extensional shear zones include the *Karmøy Shear Zone* (location in Fig. 1), which has brought the well-preserved Karmøy Ophiolite Complex (Pedersen & Hertogen 1990) in contact with the Proterozoic basement, and the *Bergen Arc Shear Zone*, which separates the arc-shaped allocthons of the Bergen area from the basement and lower nappe units to the east (Wennberg *et al.* 1998). The *Nordfjord-Sogn Detachment Zone* is another top-to-the-west shear zone that transects the Caledonian basement and will be treated below. These shear zones postdate most of the Mode I back-sliding of the orogenic wedge and represent a second mode of horizontal stretching of the Caledonian crust in western Scandinavia.

Devonian basins and the Nordfjord-Sogn Detachment Zone

The Devonian basins of SW Norway, particularly the Solund and Kvamshesten basins, were previously thought to have been thrust eastward at late stages of the Caledonian orogeny, loosely referred to as the Svalbardian and more locally the Solundian phase (e.g. Kolderup 1923; Høisæter 1971; Roberts 1983; Torsvik *et al.* 1986), but it was realized through the 1980s that abundant top-to-the-west kinematic data and condensed metamorphic isograds contradict such an interpretation (Norton 1986, 1987; Séranne *et al.*, 1989; Andersen *et al.* 1991). Instead, it became clear that what underlies the Devonian basins is perhaps one of the largest extensional shear zones in the world, now known as the Nordfjord-Sogn Detachment Zone.

The Nordfjord-Sogn Detachment Zone (NSDZ) is the largest of the west-dipping extensional shear zones in the Scandinavian Caledonides in terms of strain, offset and thickness. This shear zone, which is generally a very low-angle detachment zone that probably initiated with steeper dips, is seen to be curved around east–west axes that plunge very gently to the west. The NSDZ stretches for 120 km from the north side of the Devonian Hornelen Basin to the outer Sognefjord area, where it connects with the Bergen Arc Shear Zone. The Nordfjord-Sogn Detachment Zone separates the Devonian basin fill and its greenschist-facies substrate in the hanging wall from eclogite-bearing gneisses of the Western Gneiss Region in the footwall (Fig. 8), a metamorphic break that increases to the north because of the NW-directed *P-T* increase in the Western Gneiss Region (Krogh 1977; Young *et al.* 2007).

Internally, the zone comprises a highly attenuated series of reworked Baltican basement, continental nappes and oceanic nappe units, all strongly sheared and with abundant top-to-the-west kinematic indicators (Chauvet & Séranne 1988). The extension-related metamorphic grade increases downwards through the zone from greenschist to amphibolite facies, although retrogression and finally overprinting by brittle structures are characteristic throughout. Discrete detachments of brittle character that locally excise the ductile detachment zone are late components of the Nordfjord-Sogn Detachment Zone (Braathen *et al.* 2004; Johnston *et al.* 2007*a*), with Permian and even late Jurassic to Early Cretaceous activity (Eide *et al.* 1997). Such brittle detachments typically mark the upper margin of the detachment zone, while the lower boundary tends to be more gradual. The Nordfjord-Sogn Detachment Zone is up to 5–6 km thick, indicating an offset well in excess of 50 km (Norton 1986; Milnes *et al.* 1997). However, the total ductile shear offset is complemented by more coaxial deformation in its footwall (Andersen & Osmundsen 1994), a finding that has caused a change from models involving just the detachment zone itself to more composite models that also involve flow in the lower crust, as represented by the basement gneisses of the Western Gneiss Region.

The clastic Devonian basins in the hanging wall to the NSDZ rest unconformably on Lower Palaeozoic rocks of the Upper Allochthon, and are in fault contact with the detachment zone along their northern, eastern and southern margins. The only exception is the smallest of the basins (Håsteinen), which rests unconformably on allochthonous rocks of the hanging wall to the NSDZ (Vetti 2008). The development of these supradetachment basins is clearly connected to the NSDZ, although they initiated in the hanging wall to a normal fault system east of their present location and were later juxtaposed against the ductile NSDZ. Their large stratigraphic thicknesses, more than 25 km for the northern (Hornelen) basin, has been explained by a listric fault model that also explains the general easterly dip of the Devonian beds (Figs 2b–d).

Coaxial strain and (U)HP beneath the Nordfjord Sogn Detachment Zone

High Caledonian pressures are indicated by eclogites and related high-P parageneses in the western part of the Western Gneiss Region, increasing to ultrahigh pressure (UHP) assemblages (coesite and micro-diamonds) north of the Hornelen Basin (Fig. 8). The eclogite-bearing gneisses show a general trend of increasing P–T conditions toward the NW (Krogh 1977; Labrousse *et al.* 2004; Young *et al.* 2007). In detail, however, this trend is complicated by incomplete metamorphic equilibration and by late ductile deformation of the Western Gneiss Region. The influence of ductile deformation increases to the NW towards the Møre-Trøndelag Fault Zone, which had a significant Devonian strike-slip component (Séranne 1992*b*; Robinson 1995; Krabbendam & Dewey 1998).

Exhumation of these UHP rocks from as much as 100–140 km depth (Wain 1997; Cuthbert *et al.* 2000; Terry *et al.* 2000*a*) to upper crustal levels over a relatively short period of geological time is challenging, and shear along the NSDZ may not be the only mechanism involved. There is evidence of coaxial and for a large part constrictional strain in the WGR beneath the NSDZ that have contributed to the E-W extension (Krabbendam & Wain 1997; Barth *et al.* 2010). This deformation occurred under amphibolite-facies conditions, and thus at crustal depths (Krabbendam & Wain 1997). Furthermore, several authors have presented variations of a model involving coaxial or more complex flow at sub-crustal depths where a marked density contrast is to be expected between the weakened and buoyant leading edge of subducted continental crust and the surrounding mantle, and simple shear on the NSDZ at crustal levels (Andersen *et al.* 1995; Milnes *et al.* 1997; Hacker 2007; Johnston *et al.* 2007*b*; Young *et al.* 2007). Geochronological data indicate that this sub-crustal flow predates the NSDZ (Johnston *et al.* 2007*a*).

Time constraints in SW Norway

The youngest sediments evidently affected by Caledonian thrusting in the Caledonides belong to the Ludlow and lower Pridoli (423–418 Ma) Ringerike Sandstone of the Oslo region (Bockelie and Nystuen, 1985). $^{40}Ar/^{39}Ar$ dates of cleaved phyllite from the hinterland indicates that the Caledonian collision was ongoing at *c.* 410 Ma (Fossen & Dunlap 2006). Similarly, samples with fabrics consistent with foreland-directed thrusting from the décollement along the eastern margin of the Jotun Nappe yield $^{40}Ar/^{39}Ar$ ages within the range 415–408 Ma, while muscovite $^{40}Ar/^{39}Ar$ ages from samples with hinterland-directed (extension-related) fabrics from the same area fall between 402–394 Ma (Fossen & Dunlap 1998), suggesting a change from convergent to divergent movements a few million years before 400 Ma.

Muscovite $^{40}Ar/^{39}Ar$ ages from the Western Gneiss Region (Lux 1985; Chauvet & Dallmeyer 1992; Andersen *et al.* 1998; Hacker & Gans, 2005; Root *et al.* 2005; Walsh *et al.* 2007; Young *et al.* 2007) span from around 400 Ma in the SE to 390–365 Ma in the NW UHP area. They are generally regarded as cooling ages reflecting the north-westerly dip of the subducted WGR in the Middle Devonian (e.g. Walsh *et al.* 2007), where the deepest parts were the last to pass the $^{40}Ar/^{39}Ar$ retention temperature. These $^{40}Ar/^{39}Ar$ ages mostly postdate U–Pb and Sm–Nd ages of the (U)HP metamorphism, which range from 415–400 Ma (Mearns 1986; Mørk & Mearns 1986; Terry *et al.* 2000*b*; Carswell *et al.* 2003; Root *et al.* 2004; Tucker *et al.* 2004; Young *et al.* 2007). Hence, the UHP metamorphism occurred before, but also during the initiation of the NSDZ and the regional switch from Caledonian contraction to postcollisional extension in this part of the Caledonides. Late Ordovician (446–449 Ma) white mica $^{40}Ar/^{39}Ar$ ages in the hanging wall to the NSDZ (Andersen *et al.* 1998; Eide *et al.* 1999) implies that the hanging wall was not buried deep enough during the Scandian orogeny to open the $^{40}Ar/^{39}Ar$ system in white mica (*c*. 350 °C). This is consistent with the model where the hanging wall to the NSDZ and the former basal thrust zone remains a relatively constant crustal depth while the WGR (footwall) is subducted to extreme depths and then educted.

The Devonian basin fill above the NSDZ is generally Middle Devonian (385–398 Ma) (Jarvik 1949), but the lowermost parts may locally contain Early Devonian (pre-398 Ma) fossils (Kiær 1918). Hence, the Devonian basin formation in SW Norway can be linked in time to top-to-the-west shearing on the extensional NSDZ. However, the basins evolved at a higher crustal level and were brought in contact with the ductile mylonites during the evolution of the NSDZ, partly as late as the Permian (Eide *et al.* 1997). K-feldspar $^{40}Ar/^{39}Ar$ modelling data from across the south Norwegian Caledonides indicates rapid cooling through the brittle-ductile transition in the Early Devonian, followed by a period of slower cooling in the south (Dunlap & Fossen 1998) and rapid cooling in Late Devonian–Early Carboniferous time in the NSDZ area (Eide *et al.* 1999). This is in agreement with U–Pb ages of epidote on brittle fault surfaces from the basement in the Bergen area (*c*. 395 Ma: Larsen *et al.* 2003).

Contraction of Devonian basins and the NSDZ

A series of upright folds with east–west trending axial trace occur from Bergen to the Møre-Trøndelag Fault Zone (Fig. 8), affecting the Devonian basin and the NSDZ, losing definition east of the coastal area. The folds are the last ductile deformation recorded in this part of the Caledonides, and their origin and precise age have been a matter of uncertainty and debate for some time. Several workers argue that the folding is syndepositional (Bryhni & Skjerlie 1975; Chauvet & Séranne 1994) and simultaneous with the development of the ductile fabrics of the NSDZ (Krabbendam & Dewey 1998), that is, north–south shortening during east–west extension. This is compatible with the observation of minor soft-sediment reverse faults in the Middle Devonian deposits. Most faults, however, have cataclastic fault rocks, suggesting north–south shortening also at later stages (Osmundsen *et al.* 1998). Some of these faults are reverse, involving offsets up to at least several hundred metres according to Braathen (1999). The development of cataclasites on these faults suggests 5–10 km burial depth during faulting.

There are other indications that at least some north–south contraction occurred after deep burial of the Devonian basin fill, including an axial planar cleavage, which is locally developed in the Håsteinen Basin (Vetti 2008), and the fact that Devonian rocks along the Møre-Trøndelag Fault Zone show growth of phengite associated with tectonic cleavage formation (Bøe *et al.* 1989). The rapid burial of Devonian sediments in the Middle Devonian, with cooling occurring in the Late Devonian (Eide *et al.* 1999), indicates that these contractional structures still could have formed during the Middle Devonian basin formation.

Some (Braathen 1999; Osmundsen & Andersen 2001; Torsvik *et al.* 1988) prefer a Late Devonian-Early Carboniferous age for the north–south contraction, partly based on paleomagnetic data presented by Torsvik *et al.* (1988). However, their paleomagnetic data do not really favour a Carboniferous age over a Devonian one (Vetti 2008), and a Late Devonian age was actually favoured on other works by Torsvik *et al.* (1986, 1987). Eide *et al.* (1997) presented thermochronologic data that indicate latest Devonian to Early Carboniferous cooling, and speculate that the cooling may be connected to a phase of folding and inversion. All together, there are indications for folding during as well as after the ductile activity on the extensional NSDZ, but we do not really know whether the north–south contraction was a prolonged Devonian feature (Chauvet & Séranne 1994) or if it occurred in the form of recurring related or unrelated pulses.

A syn-extensional model is consistent with a model where the east–west trending folds are part of a transtensional system associated with the Møre-Trøndelag Fault Zone with increasing vorticity towards the fault zone (Krabbendam & Dewey 1998). Rotation of axial traces and tightening of folds from east–west to SE–NW towards this fault zone (Chauvet & Séranne 1994; Robinson 1995) as well as a spatial rotation of the extension direction (Fig. 8) (Krabbendam & Dewey 1998) makes variants of this model compelling. It also fits the regional model presented for the North Sea Devonian basins in Figure 3. Another model is one where the north–south shortening is a completely separate event controlled by external forces and events, such as the Hercynian orogeny (Roberts

1983). A third explanation calls for internal permutations in stress axes during the development of large extensional shear zones such as the NSDZ (Yin 1991; Fletcher *et al.* 1995). Chauvet & Séranne (1994) applied this model to SW Norway, but suggested that the north–south shortening is caused by a combination of external forces and internal stress permutations during extensional exhumation.

Extensional structures in central and northern Norway

The strike-slip dominated Møre-Trøndelag Fault Zone transferred strain to several west and SW-dipping extensional shear zones to the northeast (Séranne 1992*b*), notably the Høybakken Detachment, Kollstraumen detachment zone, and the Nesna Shear Zone, and as such represents an important transfer structure in the extensional detachment system of the Scandinavian Caledonides. These shear zones are kinematically coherent and consistent with a (West)SW–(East)NE extension direction, that is, somewhat oblique to the east–west extension direction recorded in the WGR and NSDZ to the south, and show a development from plastic to brittle deformation mechanisms. At least some of them transect the basal thrust and penetrate the basement, thus postdating Caledonian thrusting. ^{40}Ar/^{39}Ar ages indicate activation around 400–380 Ma (Eide *et al.* 2002; Kendrick *et al.* 2004) with an indication of renewed extension in the Carboniferous. Also, these shear zones display an evolution from plastic to ductile deformation, with plastic conditions close to 400–395 Ma and brittle conditions closer to 380 (Larsen *et al.* 2002; Kendrik *et al.* 2004).

Extension-related structures are also present farther north, but these are not as well studied as in central and southern Norway. No major extensional detachment zone with a significant associated jump in metamorphic grade has been documented in northern Norway. There are however asymmetric folds and other kinematic structures indicating top-to-the-west transport in deformed Caledonian rocks, particularly in the Ofoten area (Steltenpohl & Bartley 1988). Fossen & Rykkelid (1992) and Rykkelid & Andresen (1994) suggested the presence of west-dipping extensional shear zone of the Mode II type described from southern Norway, but with a lesser amount of extension than that of the major shear zones in southern Norway.

The possible existence of a larger extensional décollement zone west of the present coastline in the Lofoten area (Fig. 1) has been suggested (Coker *et al.* 1995), and basement rocks containing Caledonian eclogites in the Lofoten basement window (Steltenpohl *et al.* 2003) may fit into such a model. However, the uplift history in Lofoten was much slower and/or occurred later than the one revealed in the Western Gneiss Region, with white mica ^{40}Ar/^{39}Ar cooling ages ranging from Early Devonian to Permian (Steltenpohl *et al.* 2004). It has also been suggested that substantial sinistral orogen-parallel movement of postorogenic age took place in North Norway (Steltenpohl *et al.* 2004), although the significance of this deformation is as yet unclear. Extensional structures of Devonian age may possibly be traceable somewhat farther north, to the Tromsø area, but they do not appear to be major extensional structures. Devonian extensional detachments have not been found in the northernmost part of Norway.

Discussion

A variety of extensional expressions are found in the Caledonian orogen, but those associated with the terminating stages of the orogeny dominate. These can be separated into:

1. reactivation of Caledonian thrusts or thrust zones;
2. Extensional shear zones transecting the Caledonian nappe stratigraphy and extending deep into the basement;
3. Brittle faults postdating crystal-plastic shearing; and
4. Devonian basin formation.

The formation of extensional structures is well known to occur throughout the lifetime of an orogenic cycle, particularly at higher levels of the orogenic wedge (e.g. Platt 1993). Evidence for syncollisional extension before *c.* 405 Ma is well documented in Greenland (Hartz *et al.* 2001; Andresen *et al.* 2007) and almost certainly occurred within an overall contractional orogenic wedge throughout the orogen as various wedge instabilities formed due to changing internal and external conditions (Platt 1993). A concentration of synorogenic extensional structures in Greenland may relate to the Silurian heating of this part of the orogen, as thermal weakening of thick crust is thought to promote extensional collapse (e.g. Lachenbruch & Morgan 1990; Kapp *et al.* 2008). However, in the case of the Caledonides, relative and absolute ages suggest that the majority of extensional structures were active around 400–380 Ma, followed by brittle (re)activation on both sides of the suture. The abundance of extensional deformation around 400–380 Ma indicates that the Caledonian orogen had entered a very different kinematic stage. Some have considered this a postcollisional stage (Fossen 1992, 1993, 2000; Rykkelid & Andresen 1994; Wilks & Chutbert 1994; Milnes *et al.* 1997; Rey *et al.* 1997; Krabbendam &

Dewey 1998; Johnston *et al.* 2007*b*) while others have argued in favour of synconvergent extension (Andersen *et al.* 1991; Andersen 1993; Gee *et al.* 1994; Coker *et al.* 1995; Robinson 1995). An extreme view is taken by Tucker *et al.* (2004) who present a model where (strike-slip assisted) Scandian contraction lasts well into the Late Devonian.

In this context is important to realize that the kinematic information about the Devonian extensional deformation from both sides of the North Atlantic Ocean reveals an overall pattern of dominantly top-to-hinterland transport (Fig. 1), that is, a dominance of west-directed translations of hanging walls to detachments in the Scandinavian Caledonides and east-directed translations in the Greenland Caledonides. In detail the pattern is more complex, with a more southwesterly transport direction in central Norway north of the Møre-Trøndelag Fault Zone and locally a southerly component immediately north of the Devonian basins in Greenland and additional strike-slip zones. Nevertheless, the overall hinterland-directed transport implied by the kinematic observations is remarkable.

Advocates of syn-collisional extension in the Caledonides and similar orogenic belts have explained extension in terms of gravity-driven orogenic collapse of an overthickened crust (e.g. Andersen & Jamtveit 1990). In the simplest form, such a model predicts transport of extensional allochthons toward the foreland, that is, opposite to what is generally observed in the North Atlantic Caledonides (Fig. 1). Such a simple orogenic collapse can admittedly result in top-to-hinterland normal faults or detachments in zones of extrusion or channel flow (Godin *et al.* 2006). Channel flow was proposed to explain structural and isotopic data in the Fjordland region by Hartz *et al.* (2001) and has been suggested for the Himalaya orogen (e.g. Law *et al.* 2006). However, this type of orogenic collapse-related flow is restricted to a channel or wedge where the shear at its base is constantly toward the foreland.

Kinematically such extrusion or channel flow may have occurred during the building of the Caledonian orogenic belt, but at 400 Ma it is at odds with the top-to-hinterland movement on the basal detachment zone in South Norway. As correctly hinted by Young *et al.* (2007), and illustrated in Roberts (2003, fig. 7b), syn-contractional extension would require the décollement zone (sole thrust) in southern Norway to be underlain by a deeper basal thrust with foreland-directed movement during the extensional backsliding. Such a thrust would have to extend to the foreland of the orogen, but detailed surface mapping and studies of deep seismic lines (Hurich & Kristoffersen 1988; Gabrielsen *et al.* 2009) in southern has so far failed to demonstrate such a structure. Furthermore, two or more vertical levels of simultaneously active (around 400 Ma) extensional detachments, as described from the Greenland Caledonides (Gilotti & McClelland 2008) are difficult to explain in terms of channel flow. Finally, extensional shear zones or faults that transect the thrusts and the base of the orogenic wedge, as documented in Norway and also described from Greenland, are inconsistent with an extensive extrusion or channel flow model around 400 Ma. Thus, it is hard to see how the given kinematic data and geometry of the extensional structures formed around 400 Ma and later could have formed in a regime of plain convergence between Greenland and Scandinavia.

Another remarkable characteristic revealed by Figure 1 is the apparent concentration of extensional

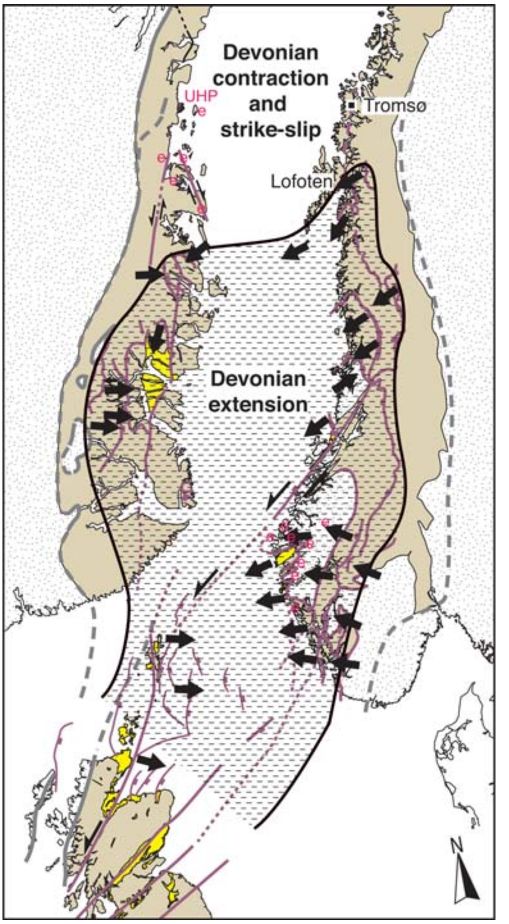

Fig. 9. Extensional transport directions and distribution of *c*. 403–380 Ma extension in the North Atlantic Caledonides. Data from Fossen (1992), Kendrick *et al.* (2004) and Gilotti & McClelland (2008).

structures to the central and southern part of the North Atlantic area (Fig. 9). In Greenland, extensional detachments of Devonian age have not been reported north of Bessel Fjord (see Fig. 5 for location). In Norway, the northernmost well-documented extensional detachment occurs in the Lofoten area. A steep fault may run northward from this area to Tromsø (Rykkelid & Andresen 1994), but this fault may be of younger age. Regardless, no Devonian extensional detachment structures are reported from northernmost Norway. Hence, the present data indicate that Devonian extension in the form of significant extensional detachment faulting is restricted to the central and southern part of the North Atlantic region.

The 360–350 Ma ages of UHP metamorphism reported from NE Greenland (Gilotti *et al.* 2004; Lang & Gilotti 2007) appear to be incompatible with a model involving a shift from contractional orogeny to whole-sale extension around or shortly before 400 Ma, or with any other model presented for the termination of the Caledonian orogeny. While it feels uncomfortable to completely rewrite the Devonian history of the North Atlantic Caledonides based on radiometric ages from a single limited field area, we shall here accept Gilotti *et al.*'s interpretation of these ages as representing evidence of continental subduction at the end of the Devonian and possibly into the Carboniferous.

Extension in the central and southern Greenland Caledonides with simultaneous continental subduction in NE Greenland can, with some difficulties, be explained by clockwise rotation of Greenland relative to Scandinavia with a pivot point near the northern part of the extensional area (Fig. 10). A clockwise rotation of Laurentia has been suggested

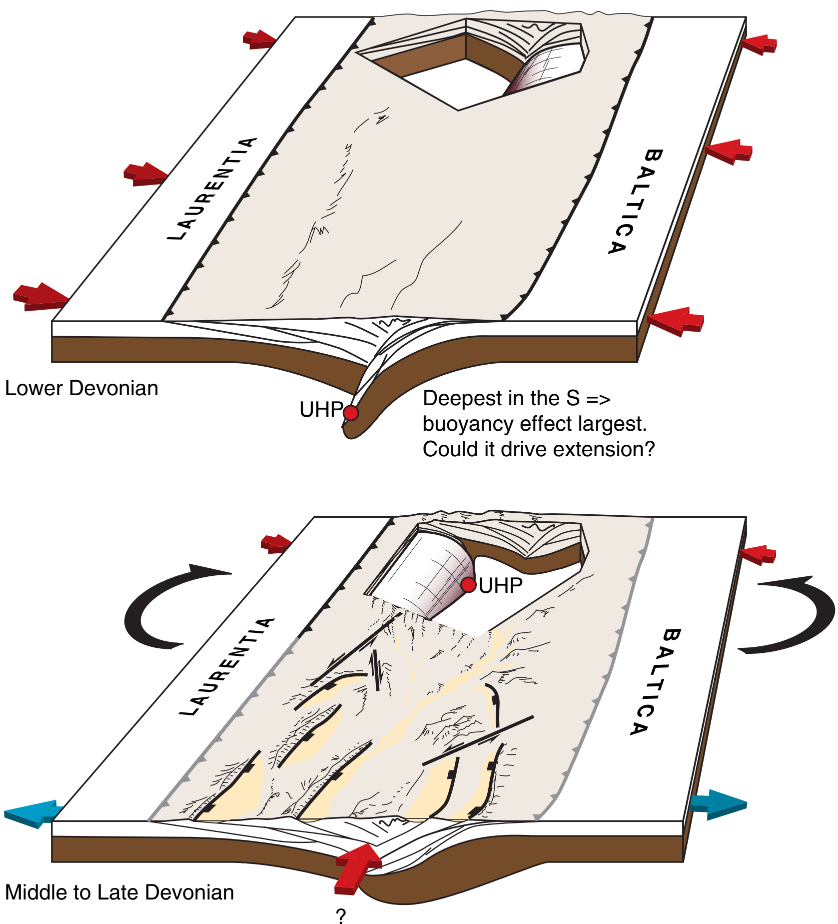

Fig. 10. Speculative model that seeks to reconcile regional extension in the southern part of the Caledonides with contemporaneous subduction in the NE Greenland Caledonides.

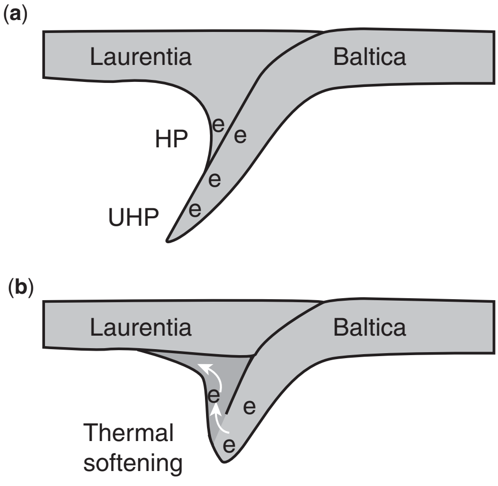

Fig. 11. Two simple models for the formation of eclogite in the Greenland Caledonides. (**a**) Dragging of the Laurentian margin to eclogite-facies conditions. (**b**) Westward subcrustal flow of heated Baltica crust.

for the Devonian-Carboniferous Hercynian/Variscan orogeny (Shelley & Bossiére 2000), and a possible relationship between continent–continent collision in the Variscides and extension in the Caledonides has already been pointed out (Rey *et al.* 1997). It is possible that a push from the south could cause divergence in the southern part of the North Atlantic region with contraction persisting in the north. This may well be associated with strike-slip movements (e.g. Dewey & Strachan 2003) if a change from transpression to transtension occurred in the south, but not (or much later) in the north. The challenge is the significant amount of contraction that is needed to form continental subduction of continental crust to ultrahigh pressure conditions. Clearly more structural as well as isotopic data are needed from the NE Greenland Caledonides to further explore this issue.

It may also be challenging to explain the simultaneous *c*. 405–400 Ma formation of eclogites in Liverpool Land and the Western Gneiss Region. Double-sided (symmetric) subduction in natural collision zones can be modelled numerically, but are uncommon or nonexistent in nature (Gerya *et al.* 2008) and therefore not a satisfactory explanation. However, drag of the edge of Laurentia down the subduction zone cannot be precluded (Fig. 11a). Another explanation may be that the Liverpool Land eclogite-bearing gneisses represents a portion of Baltica crust that remained attached to Laurentia after the rifting and opening of the Atlantic Ocean, as suggested by Augland *et al.* (2009). Several mechanisms may be inferred, one of which involves gravity-driven lateral (westward) flow of crustal material in the lower part of the subducted edge of Baltica driven by gravity (Fig. 11b), a model suggested and referred to as 'upward collapse' by Milnes *et al.* (1997). Variations of such models can be envisaged (Young *et al.* 2007; Johnston *et al.* 2007a), but at this point the choice of model relies on theoretical models rather than hard geological data.

In summary, extensional deformation in the Caledonides was long lived, with extensional detachment faulting dating back to the Silurian in the Greenland Caledonides. Extensional deformation became much more widespread and pervasive shortly before 400 Ma, and the most impressive extensional structures and associated exhumation occurred in SW Norway, linked to extensional systems in northern Britain and central and North Norway through strike-slip dominated shear zones. The exact change from orogenic convergence to post-orogenic divergence seems to occur shortly before 400 Ma in South Norway, but more data are needed to confirm if this is representative for the entire orogen, or if the change is diachronous. In particular, more systematic geochronological and geological investications of critical areas in the relatively poorly explored northern part of the orogen are needed to address this question in more detail.

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