Orogen-parallel extension of the Caledonides in northern Central Norway: an overview

Alvar Braathen, Per Terje Osmundsen, Øystein Nordgulen, David Roberts & Gurli B. Meyer

Braathen, A., Osmundsen, P.T., Nordgulen, Ø., Roberts, D, & Meyer, G.: Orogen-parallel, extension of the Caledonides in northern Central Norway: an overview. *Norwegian Journal of Geology*, Vol. 82, pp. 225-241. Trondheim 2002. ISSN 029-196X.

Extensional shear zones of Devonian age are superimposed on the Caledonian nappe stack in northern Central Norway, where they constitute signs of extensional denudation of the orogen. They divide into either broad detachment zones, or narrow, normal-sinistral shear zones, all showing a consistent, WSW-ENE bulk stretching axis, highly oblique to the recorded Scandian thrust direction (mainly SE-directed). Characteristically, medium-grade and ductile, low-angle detachment zones truncate the nappes at a low angle, and sole out in a basal shear zone (décollement) above Fennoscandian basement which, based on metamorphic grade, was located at a middle crustal level. This décollement may have partitioned dominantly NW-SE contractional strain of the lower crust from mainly extensional tectonics in the middle-upper crust. Medium-grade detachments are succeeded by narrow, low-grade, ductile to brittle, steeper shear zones that cut deep into the parautochthonous(?) Fennoscandian basement. Later events include slight, ENE-directed thrust-inversion of some detachment and shear zones, and succeeding top-WNW and top-SW extensional faulting. The overall extension pattern probably reflects Early Devonian, near orogen-parallel extension and upper-crust extension and block extrusion, followed by deeper-seated, Late Devonian to Early Carboniferous oblique extension. Major, top-WSW, latest-Scandian extension can be attributed to plate-driven, sinistral transpression during waning stages of collision between Baltica and Laurentia. Later, top-WNW extension may reflect a post-orogenic transtensional setting of Late Devonian - Carboniferous(?) age.

A. Braathen, P.T. Osmundsen, Ø. Nordgulen, D. Roberts & G.B. Meyer, Geological Survey of Norway, 7491 Trondheim, Norway. Corresponding author – Alvar.Braathen@ngu.no.

Introduction and regional framework

Collision between Baltica and Laurentia in Siluro-Devonian time resulted in a stack of thrust sheets, the Caledonides of Scandinavia and East Greenland, which were amalgamated and thrust onto the cratons. In Scandinavia (Fig. 1), transport generally was to the southeast during the Scandian orogeny (Gee & Sturt 1985), followed by Early Devonian hinterland extension (e.g., Andersen & Jamtveit 1990; Fossen 1992, 2000; Milnes et al. 1997; Andersen 1998; Osmundsen & Andersen 2001), during the waning stages of thrusting (Terry et al. 2000a,b). Models for extension depict either initial orogenic collapse (Andersen 1998), or plate remobilisation (Fossen 1992, 2000). In this contribution, we present new data on the regional extent and significance of late- to post-Scandian structures in the area between Trondheim and Bodø of Central and northern Central Norway; a region hitherto minimally evaluated with respect to late/post-Scandian extensional processes. By filling the geographical gap in our knowledge of these structures, we pave the way for a broader discussion of processes related to extensional denudation of the Caledonides.

The denudation of collisional orogens, and especially the importance of major extensional detachments in such crustal-scale systems, has intrigued the geological community over the last two decades (e.g., Wernicke 1985; Lister & Davis 1989). This is mainly because such large shear zones can explain the juxtaposition of rocks metamorphosed in the middle-lower crust with rocks showing only an upper crustal history. A classical province for crustal-scale extension is found in western Norway. There, late/post-Scandian extensional tectonics were first identified by the recognition of the Nordfjord-Sogn Detachment (e.g., Hossack 1984; Norton 1986, reviewed in Andersen 1998), which obliquely truncates and juxtaposes lower-plate eclogites and migmatitic gneisses of the footwall against upper-plate Caledonian nappes and Devonian sedimentary basins of the hangingwall (Fig. 1b). This two-plate framework is also reflected in the deformation mechanisms recorded. Kinematic analyses of fabrics preserved in eclogites derived from a lower-crustal position and succeeding retrograde structures of such rocks as they approached and entered the detachment zone, suggest that bulk vertical flattening of the lowermost crust was synchronous with rotational (co-axial) deformation in the vicinity of the overlying detachment zone(s) (Andersen

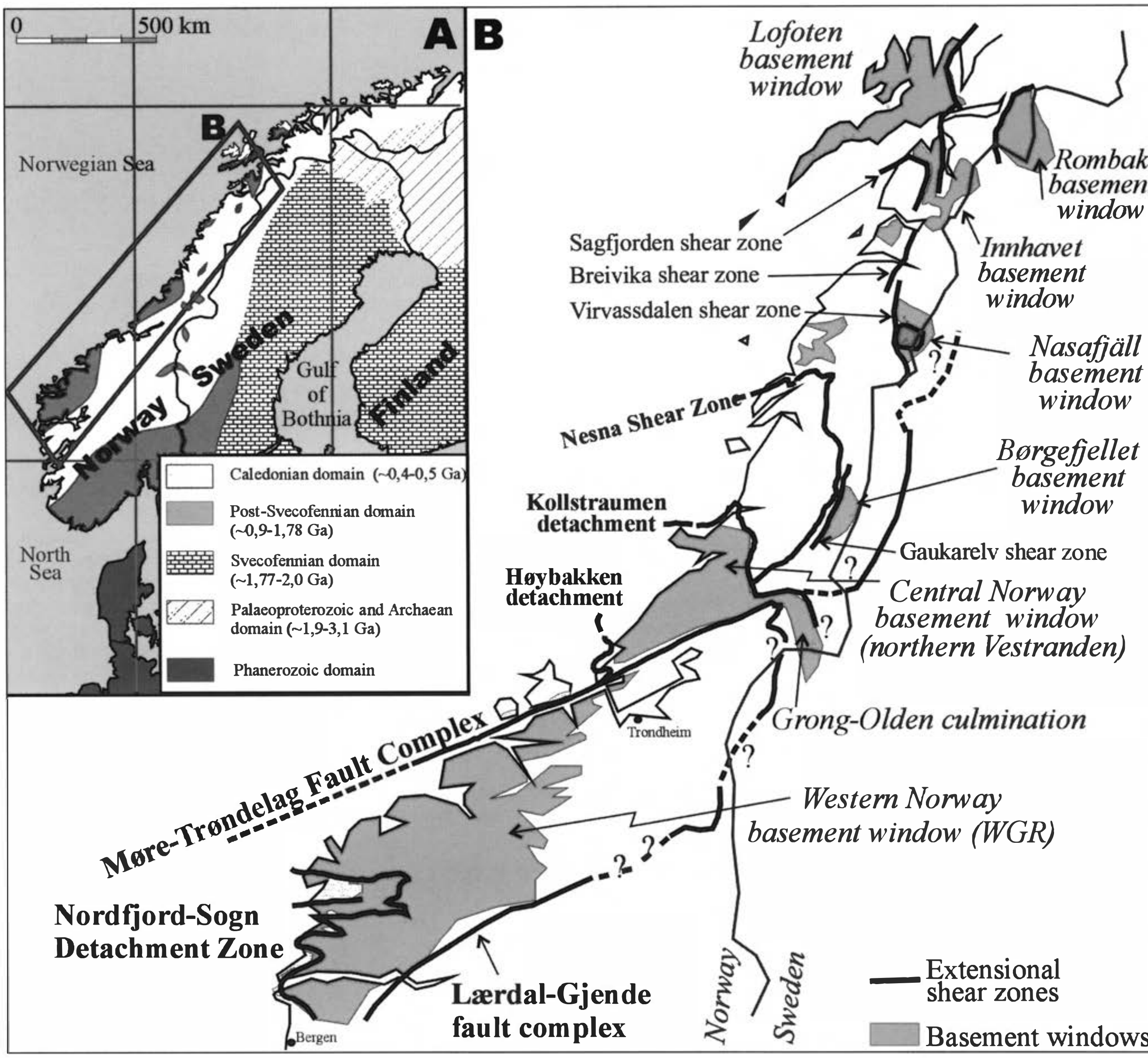

Fig. 1. (a) Map of Scandinavia with main tectonic provinces. (b) Overview map of regional, latest-Scandian, Devonian extensional shear zones and footwall basement windows. See location in Figure 1a.

& Jamtveit 1990; Andersen et al. 1994; Engvik & Andersen 2000). It is noteworthy that the stretching axis of this region was nearly E-W, i.e. almost opposite in trend and direction to the Scandian nappe emplacement (e.g., Milnes et al. 1997). Extension was also manifested by Early-Mid Devonian, low-grade, coarse-clastic rocks, deposited in E-W oriented, fault-bound basins that drape the upper-plate rocks (e.g., Osmundsen et al. 1998; Osmundsen & Andersen 2001). During and after the formation of these supradetachment basins, the entire rock column of the region was deformed into extension-parallel, regional E-W folds (e.g., Krabbendam & Dewey 1998; Osmundsen & Andersen 2001; Sturt & Braathen 2001), and later modified by Permian and Mesozoic faulting (e.g., Torsvik et al. 1992; Eide et al. 1997, 1999; Braathen 1999). The concept of synchronous extension, fold-related contraction and basin formation can be imagined through several processes, such as crustal-scale constrictional strain (Krabbendam & Dewey 1998; Osmundsen & Andersen 2001), and/or shifting stages of regional transpression and transtension related to the structural situation along the Møre-Trøndelag Fault Complex (MTFC)(Erambert & Braathen in press).

The regional change in fold trends confirms the importance of the MTFC. Northwards from Bergen, latest-Scandian folds, as well as the extensional stretching axis, gradually rotate from E-W into NE-SW trends (Roberts 1983; Robinson 1995), and folds become progressively tighter in the vicinity of the MTFC. This change in structural attitude can be seen as a gradual shift, from nearly orogen-normal extensional denudation of the Caledonides in the south, to highly orogen-oblique in the vicinity of the MTFC (Braathen et al. 2000), and northwards (see Discussion).

The onshore MTFC consists of several subvertical strands characterised by ductile sinistral movement in the Early Devonian (Séranne 1992), when it acted as a transfer zone (e.g., Braathen et al. 2000), followed by several brittle dip-slip to oblique-slip and dextral movements from the Late Devonian onwards (e.g., Grønlie & Roberts 1989; Grønlie et al. 1991, 1994; Watts 2002). Observations along the offshore extension of the fault zone verify reactivations during latest Palaeozoic and late Mesozoic basin formation on the shelf (e.g., Gabrielsen et al. 1999).

Extensional structures of northern Central Norway

In northern Central Norway, a number of major extensional detachments and shear zones have been identified the in recent years. Some have been reported in the literature (Séranne 1992; Braathen et al. 2000); others, however, are presented for the first time in this contribution. More localized descriptions can be found in Eide et al. (2002), Larsen et al. (2002), Nordgulen et al. (2002) and Osmundsen et al. (2003), whereas Olesen et al. (2002), Osmundsen et al. (2002) and Skilbrei et al. (2002) discuss the offshore extent of such detachment zones.

The Høybakken (HD of Figs. 2 and 3; Séranne 1992) and Kollstraumen detachments (KD; Braathen et al. 2000; Nordgulen et al. 2002) separate nappe rocks, draped by Devonian rocks in the southwest, from Palaeoproterozoic orthogneisses of the Central Norway basement window (CNBW). The latter locally contains high-P, granulite-facies mineral assemblages (Möller 1988). In this region, too, the entire rock column, including the detachments and the Early-Mid Devonian supradetachment basins, was folded. These folds are more pronounced in the basement windows, where supracrustal nappe rocks occur as long lobes and tongues, tightly to isoclinally downfolded into mainly granitoid gneisses. The latter rocks were significantly deformed together with the supracrustal rocks during the Caledonian Orogeny (Fig. 4a; e.g., Roberts 1998).
The uppermost tectonostratigraphic unit of northern Central Norway, the Helgeland Nappe Complex (HNC; e.g., Stephens et al. 1985; Nordgulen et al. 1993), is entirely bound by extensional shear zones - the Kollstraumen Detachment in the south, and the Nesna shear zone (NSZ) in the east and north (Osmundsen et al. 2003). These shear zones truncate the nappe sequence at a low angle and sole out above the underlying basement windows. In the footwall of the NSZ to the northwest, on Træna, eclogite-bearing basement gneisses are present (Gustavson & Gjelle 1991; Larsen et al. 2002), whereas to the east and northeast, two large gneiss-cored culminations constitute the footwall, i.e., the Børgefjell and Nasafjäll basement windows (Fig. 2). Extensional shear zones characterise the western margin of both windows (Gaukarelv and Virvassdalen shear zones - GSZ and VSZ), a situation that mimics the crustal section near Trondheim. There, signatures of a deep-crustal seismic profile indicate that narrow, extensional shear zones bound gneiss-cored culminations along their western side, cutting down to the basal Caledonian detachment (see Fig. 2 for location; Hurich et al. 1988; Hurich & Roberts 1997; Andersen 1998). Extensional structures are also documented from this area (Bergman & Sjöström 1997). The Nasafjäll window also reveals the low-angle, flexured Randal shear zone (RSZ) between possible autochthonous basement and a basement nappe of the Lower Allochthon. The RSZ may link to an extensional shear zone at the contact between the Seve-Köli Nappes farther east (S-KSZ), although Greiling et al. (1998) argue that this down-to-the-W structure formed prior to late thrusting. Northwards, the Virvassdalen shear zone steps over to the Breivika shear zone (BSZ), whereas even farther north, the Sagfjorden shear zone (SSZ) marks the southwestern margin of the Innhav basement window (or Tysfjord culmination).

The metamorphic grade and thereby the crustal level of formation of the extensional shear zones of Central and northern Central Norway vary (e.g., Lindquist 1990), as suggested by fabrics ranging from medium-grade to low-grade ductile, and even to brittle conditions. A guide to the metamorphic conditions for syn-tectonic fabrics is the appearance of garnet in mica-rich pelites, a rock-type hosted by all shear zones. Diagnostically, garnet appears in medium-grade shear zones, and is either highly retrogressed or totally replaced in low-grade zones. In order to evaluate the structural position of shear zones during extension in an orderly fashion, the described shear zones are grouped according to metamorphic grade. One has to bear in mind that this does not necessitate a strict temporal link, since the age of activation may vary from one structure to another. However, geochronological data (e.g., Eide et al. 2002) are in support of synchronous regional extension, indicating that most shear zones of any one particular metamorphic grade have a common evolution.

Strikingly, almost all mapped extensional shear zones reveal overall top-WSW transport. One exception is the Kollstraumen detachment that shows movement to the ENE (Braathen et al. 2000; Nordgulen et al. 2002). In more detail, the majority of recorded extension-related, stretching lineations plunge gently towards 250-252° (Fig. 5a-d). Poles to shear fabrics plot along great circles, which are consistent with near stretching-parallel fold axes, plunging gently between 244 and 250°. The

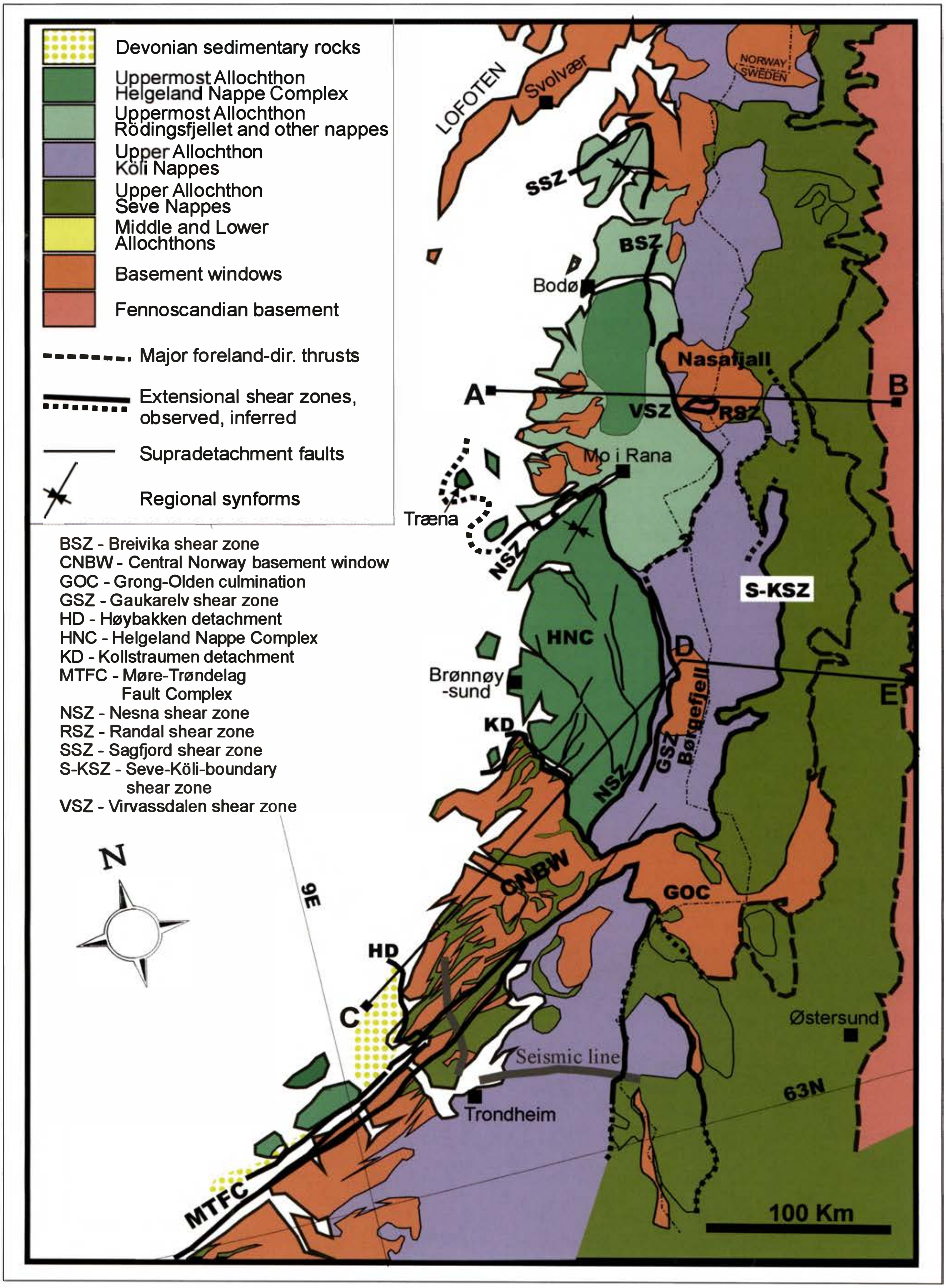

Fig. 2. Schematic bedrock map of Central and northern Central Norway and western parts of Sweden, emphasizing extensional shear zones. The locations of cross-sections are indicated, as well as the position of a seismic line discussed in the text.

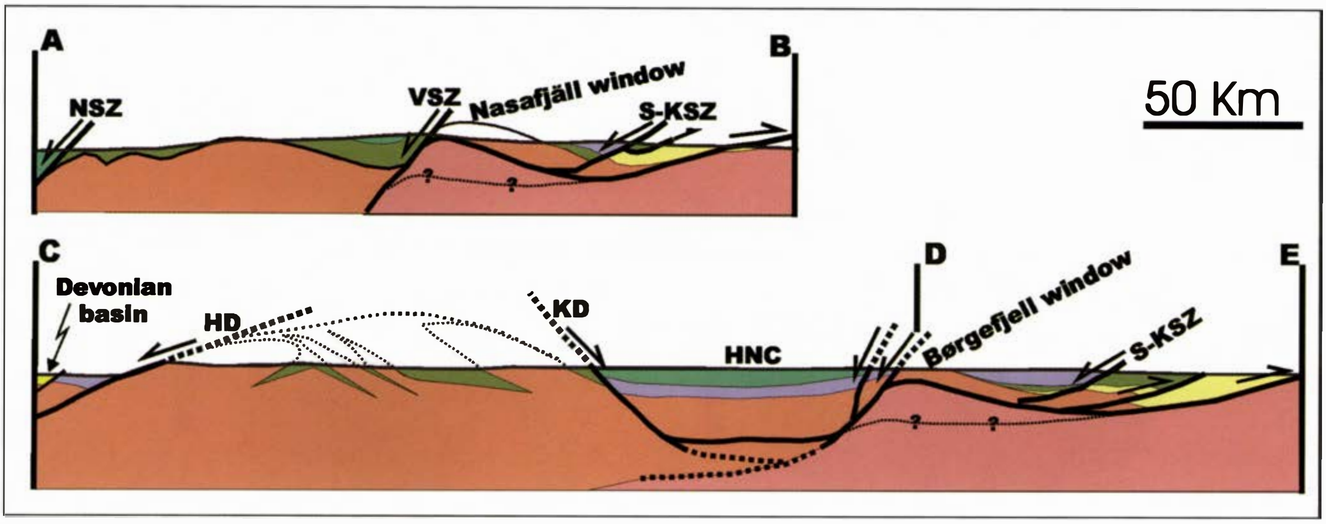

Fig. 3. Schematic cross-sections illustrating the structural style and importance of late/post-Scandian deformation. Abbreviations as in figure 2.

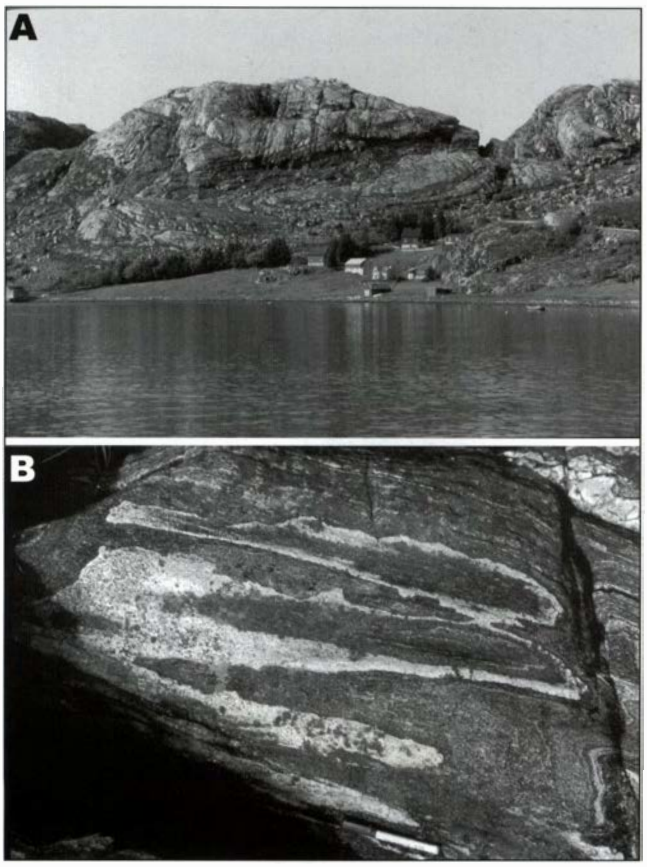

Fig. 4A. Infolded supracrustal schist with distinct layering in rather massive migmatised granodioritic gneiss of the Central Norway basement window (Vestranden); near Draugfjellet, 5 km northwest of Osen. View towards north. UTM(33) 281010-7142390. B. Isoclinal sheath-folds, elongated along the lineation of LS-tectonised mylonitic schists of the Sagfjorden shear zone. View is to the northeast. UTM(33) 507690-7531920.

identified extensional shear zones, previously regarded as thrusts or low-strain lithological contacts, clearly have a strong bearing on the location of the basement windows and the distribution and geometry of the Caledonian nappe pile. In the following, we evaluate their importance through metamorphic grade and relative and absolute age, leading to a synthesis of the late/post-Scandian extension in Central and northern Central Norway.

Medium-grade extensional shear zones

Regional scale, medium-grade shear zones (HD, KD, NSZ, RSZ, S-KSZ, and SSZ of Figs. 2 and 6) characteristically are 0.5-2 km thick. They contain a fabric that, in general, shows a marked stretching lineation (L) within a variably manifested foliation (S), i.e., varying from S>L- to L>S- and locally L-tectonised rocks. Common rock types include mylonitised garnet-bearing schists, marble and blastomylonitic orthogneisses. In the coastal basement windows and in the overlying medium-grade shear zones, metre-thick syntectonic granitic dykes are present (Braathen et al. 2000; Larsen et al. 2002; Nordgulen et al. 2002). In many places, the shear zones have retrogressed Caledonian fabrics; however, prograde metamorphism is also observed. A pronounced, WSW-plunging, stretching lineation (Figs. 4b, 5a and 7c) is defined by the long axes of elongated minerals such as mica and subordinate amphibole, pressure shadows of quartz, feldspar and subordinate mica, and platy quartz and feldspar rods. Composite shear fabrics and folds (Fig. 7a,b), winged porphyroclasts (Fig. 7d), and a distinct S-C fabric in orthogneiss are all supportive of down-to-the-WSW transport.

Most medium-grade shear zones slice through the nappe pile (HD, KD, NSZ, and SSZ of Figs. 2), e.g., the Nesna shear zone cross-cuts nappe rocks and foliations

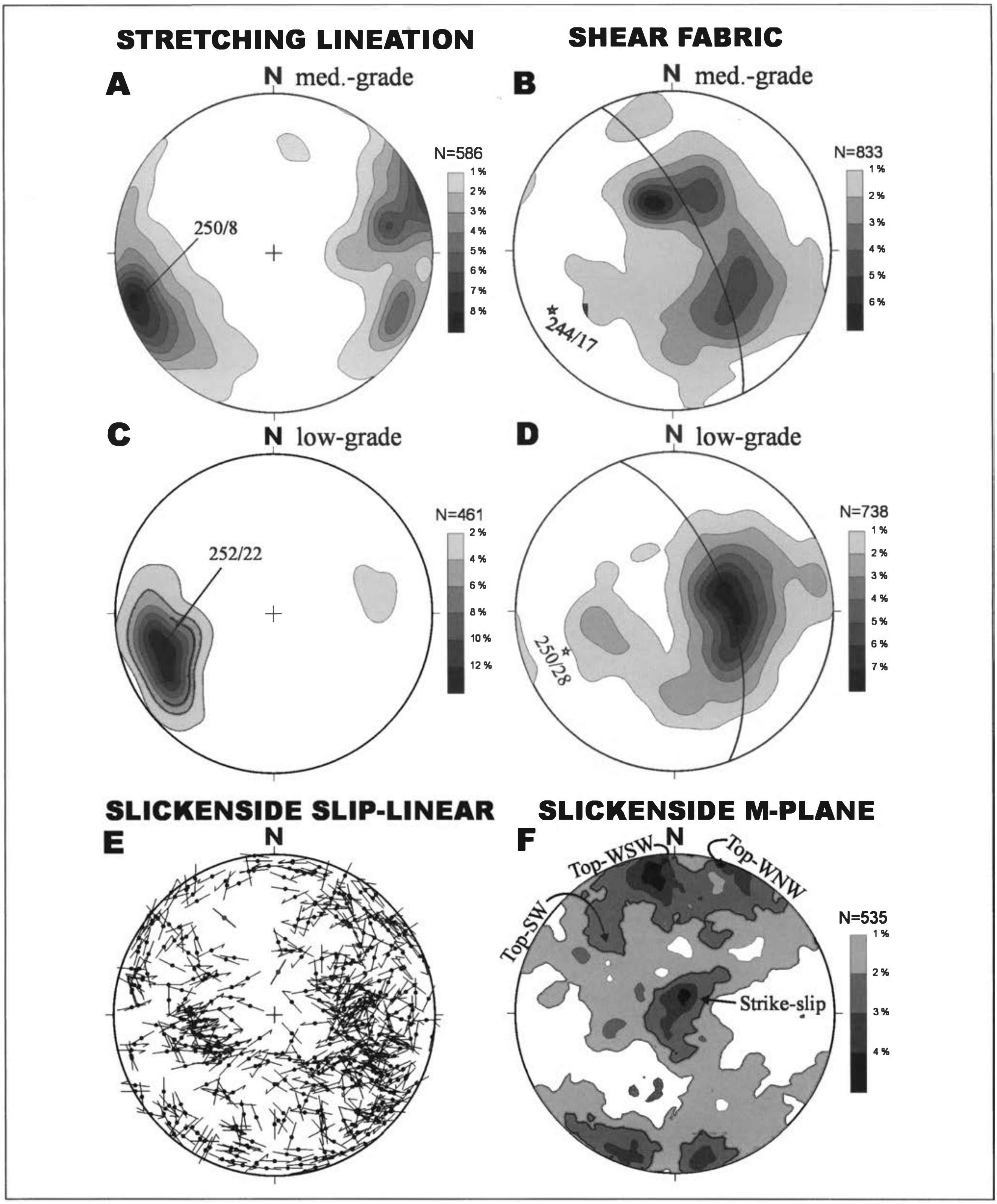

Fig. 5. Stereographic projections (equal area, lower hemisphere) of structural data collected from the region between Trondheim and Bodø. (a) Contoured stretching lineations recorded in medium-grade shear zones. (b) Contoured poles to foliation and shear bands of medium-grade shear zones. The data plot along a girdle consistent with a WSW-plunging fold axis (asterisk). (c) Contoured stretching lineations recorded in low-grade shear zones. (d) Contoured poles to foliation and shear bands of low-grade shear zones. The indicated girdle is consistent with a WSW-plunging fold axis (asterisk). (e) Slip-linear plot of faults (method described below). (f) Contoured M-plane plot based on faults in (e), with high concentrations consistent with top-WNW, -WSW and -SW normal faulting. The strike-slip M-plane domain corresponds to subvertical faults of the MTFC (Fig. 11j), intersecting the Grong-Olden Culmination. The 'slip-linear' plots, as described by Goldstein and Marshak (1988) and Braathen (1999), present the pole to the fault plane decorated by a line/arrow, which indicates the direction and sense of slip of the hanging wall. The arrow is parallel to the horizontal trace of a plane (M-plane), which is defined by the pole to the fault and the slip-line.

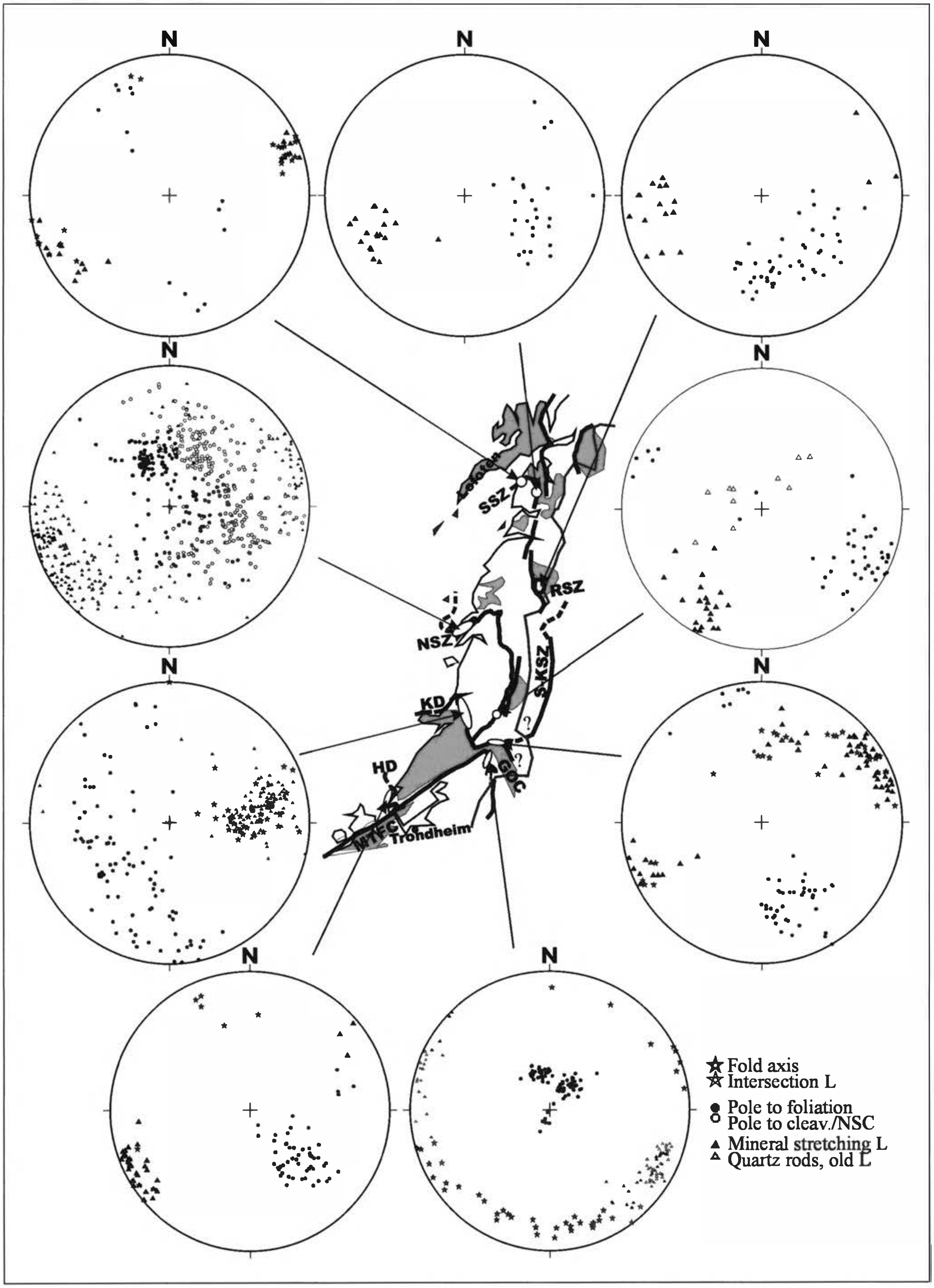

Fig. 6. Structural data from medium-grade extensional shear zones. Areas for data acquisition are approximately located.

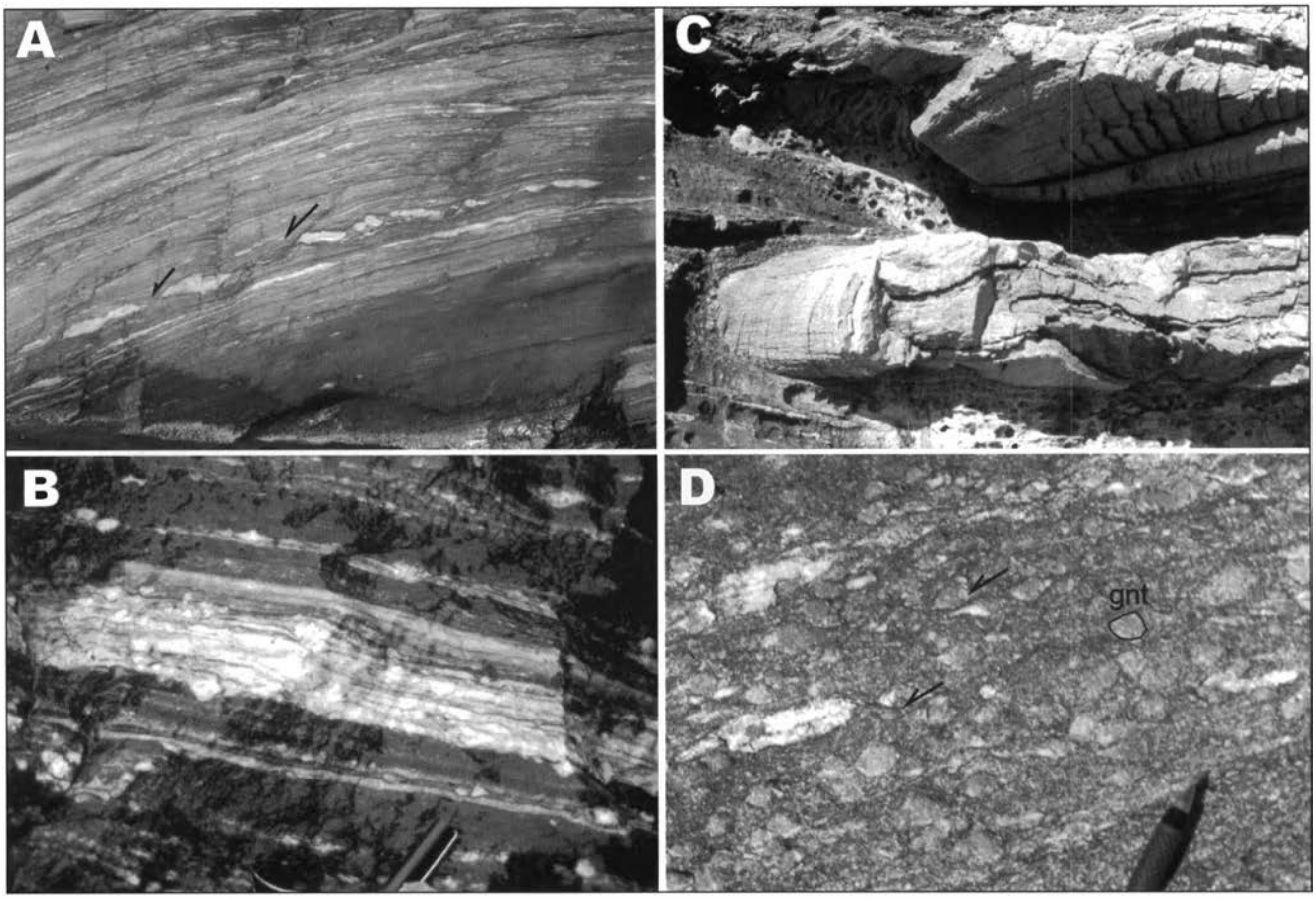

Figure 7. Examples of structures in medium-grade shear zones. (a) Well-developed top-WSW, normal shear bands, displacing a thin granitic layer of the Nesna shear zone. Location, Hugla, UTM(33) 405843-7340330. (b) Blastomylonitic, pegmatitic granitic dyke of the Kollstraumen detachment (see Braathen et al. 2000), seen from the east. The neighbouring dyke is dated to 401 Ma (Schouenborg 1988). UTM(33) 363465-7217860. (c) Granitic dykes of the Høybakken detachment, elongated along the L>S-fabric of recrystallised marbles. Note the top-WSW faulting in the granite, reflecting very high competency contrasts between marble and granite. View is to the west. UTM(32) 535385-7082700. (d) Garnet porphyroclasts in the Nesna shear zone. The garnets, one of which is marked 'gnt', participated in top-WSW shearing of the rock, seen as dark normal shear bands, without being retrogressed. Quartz-fringes around the garnets reflect pre-fabric mineral growth. UTM(33) 405842-7340292.

at a low angle, and splits the Uppermost Allochthon into two domains (Osmundsen et al. 2003). However, these shear zones do not penetrate autochthonous Fennoscandian basement, but are seen to root in a décollement zone near the top of the basement windows (Figs. 2 and 3). For example, at Nasafjäll, the top-WSW Randal shear zone is situated in the upper parts of possibly autochthonous basement granite, in the overlying thin sedimentary cover, and along the sole of the overriding basement nappe. Deformation is subparallel to the low-angle contacts, and therefore consistent with a basal décollement structure. An inferred link to the Seve-Köli shear zone (Fig. 3, cross-section C-D-E), in accordance with Thelander et al. (1980), indicates that the Randal shear zone has a low-angle, truncating character upwards through the nappes. Other examples include (i) the moderately W- and SE-dipping Sagfjorden shear zone that follows a schist unit some metres above, and parallel to, the basement contact, (ii) the Nesna shear zone that is subparallel to the margin of several basement windows (Osmundsen et al. 2003), and (iii) the moderately NE-dipping Kollstraumen detachment that follows, but nowhere cuts into the CNBW (Nordgulen et al. 2002).

The medium-grade shear zones are flexured. This is displayed at Nasafjäll, where the Randal shear zone occurs in a N-S oriented footwall culmination of the Virvassdalen shear zone (Figs. 2 and 6). Both the Sagfjord and the Nesna shear zones and their hangingwall rocks appear to be openly folded around gently WSW-plunging axes (Fig. 6) parallel to the extensional transport direction (Osmundsen et al. 2003). However, since the stretching lineation and fold axes are parallel, one could also argue that the shear zones reactivate an inherited structural grain. Culminations in the footwall of the Nesna and Sagfjorden shear zones reveal vague long axes of approximately NW-SE trend, which roughly mimic the strike of the overlying shear zones. This is consistent with uplift of the culminations as a result of extensional movement on the shear zones (Eide et al. 2002; Larsen et al. 2002).

Extension-parallel folds, in general, are rare in the footwall of the shear zones, albeit some supracrustal rocks are tightly down-folded into basement culminations along a similar orientation. An exception is the area around the CNBW, where the Kollstraumen and Høybakken detachments were involved in the intense folding of the footwall. The detachments are openly folded in strike-parallel sections and appear to be thicker in the synforms. Two plausible reasons for this are; (i) either fold decapitation, as shear activity rejuvenated the upper part of the detachment zone, or (ii) synchronous shear and folding, where shear activity gradually migrated and focused towards the top of the shear zone during folding. These folds can be traced into the footwall, where amplitudes increase; and synforms of nappe rocks are tight to isoclinal (Fig. 4a). It is suggested that they initiated during Scandian contraction, as discussed by Nordgulen et al. (2002). Characteristically, all such fold axes are near parallel to the extension direction and normal to the overall Caledonian thrusting direction. They are also parallel to the folds in the Devonian basins above the Høybakken detachment (Braathen et al. 2000). With folding of these latest-Scandian, supradetachment basins in mind, one can conclude that there is a temporal overlap between extensional shear and some of the contraction seen as extension-parallel folding.

Low-grade shear zones

Low-grade shear zones are 100-300 m thick and typically consist of S- to S>L-, and subordinate L>S-tectonised, micaceous mylonite and mylonitic marble. They are in many cases retrograde, as suggested by host-rock garnet and subordinate kyanite, which has broken down to mainly mica, chlorite and quartz. In the shear zones, the stretching lineation represented by oriented mica and rods of sheared-out quartz and calcite veins plunges to the WSW (Figs. 5c and 8). Composite shear fabrics and folds, veins and locally semi-ductile faults (Fig. 9a,b) consistently support overall top-WSW transport.

The low-grade shear zones (GSZ, VSZ and BSZ of Figs. 2 and 3) truncate both Caledonian nappes and their subjacent basement. This is well displayed in the Nasafjäll and Børgefjell basement windows, both bound in the west by moderately (30-50°) WSW-dipping shear zones that cut down from the nappe rocks into the basement gneisses. The footwall domains are flexured into large N-S, double-plunging antiforms. Several of the medium-grade shear zones show evidence of low-grade shear reactivation as well. The southeastern part of the Kollstraumen detachment, for example, is characterised by an approximately 100 m-wide shear zone comprising retrograde, semi-ductile shear bands and faults (Fig. 9b), which truncates the southernmost part of the Nesna shear zone (see Fig. 2). Faults also cut into the Grong-Olden culmination (GOC). This low-grade deformation style may correlate with localised ductile shearing in marbles within the detachment farther west, as suggested by large, mainly brittle faults in the Helgeland Nappe Complex of the hangingwall that have listric geometries towards their roots in these marbles. These faults transect all Caledonian structures (Fig. 2; Ihlen 1993), and show several generations of semi-ductile to mainly brittle fault-rocks, ranging from old, green-grey phyllonite/mylonite and cataclasite to late, zeolite-cemented breccia, and gouge (Fig. 10c). Marble is an important strain localiser also in other shear zones (for example Figs. 7c and 9a), e.g., in both the Høybakken detachment and the Nesna shear zone, such rocks are associated with late shearing (Braathen et al. 2000; Osmundsen et al. 2003).

Late, brittle faulting

Several of the ductile and semi-ductile shear zones are reactivated by late, mainly brittle faults (HD, KD, GSZ, NSZ), as shown in Fig. 10a. The best example is found at Børgefjell, where an anastomosing network of cm-wide shear bands with very fine-grained foliated cataclasite transects the main, top-WSW mylonitic fabric (Fig. 9c,d). Two populations of shear bands have been observed, with disparate movement directions revealed by drag-folds, weakly developed stretching lineations, and slickenlines. Cross-cutting relationships indicate that the main, top-WSW shearing on ductile shear bands and semi-brittle faults was succeeded by subordinate, dextral-normal, top-WNW movement, prior to sinistral-normal, top-SW transport (Fig. 11 e,f).

Strikingly, within the northern Nesna shear zone and along the Breivika shear zone, there are small, brittle thrusts that partly invert the top-WSW normal shear bands (Fig. 10b). Locally, they are associated with E-verging kink-folds. Transport on the thrusts is towards ENE (Fig. 11a,b,c,d), and besides, they are locally rejuvenated as top-WNW normal faults. In summary, late brittle structures chronologically divide into ENE-directed thrusts, top-WNW normal faults, and top-SW normal-sinistral faults (Fig. 5e,f).

Timing of extension in northern Central Norway

When recent geochronological studies (Eide et al. 2002; Larsen et al. 2002; Nordgulen et al. 2002) are summarised in the light of previously published ages, a rough temporal framework emerges: (i) Orogen-parallel extensional denudation of the northern Central Norwegian Caledonides may have started as early as 420-410 Ma, which indicates a temporal link with the Scan-

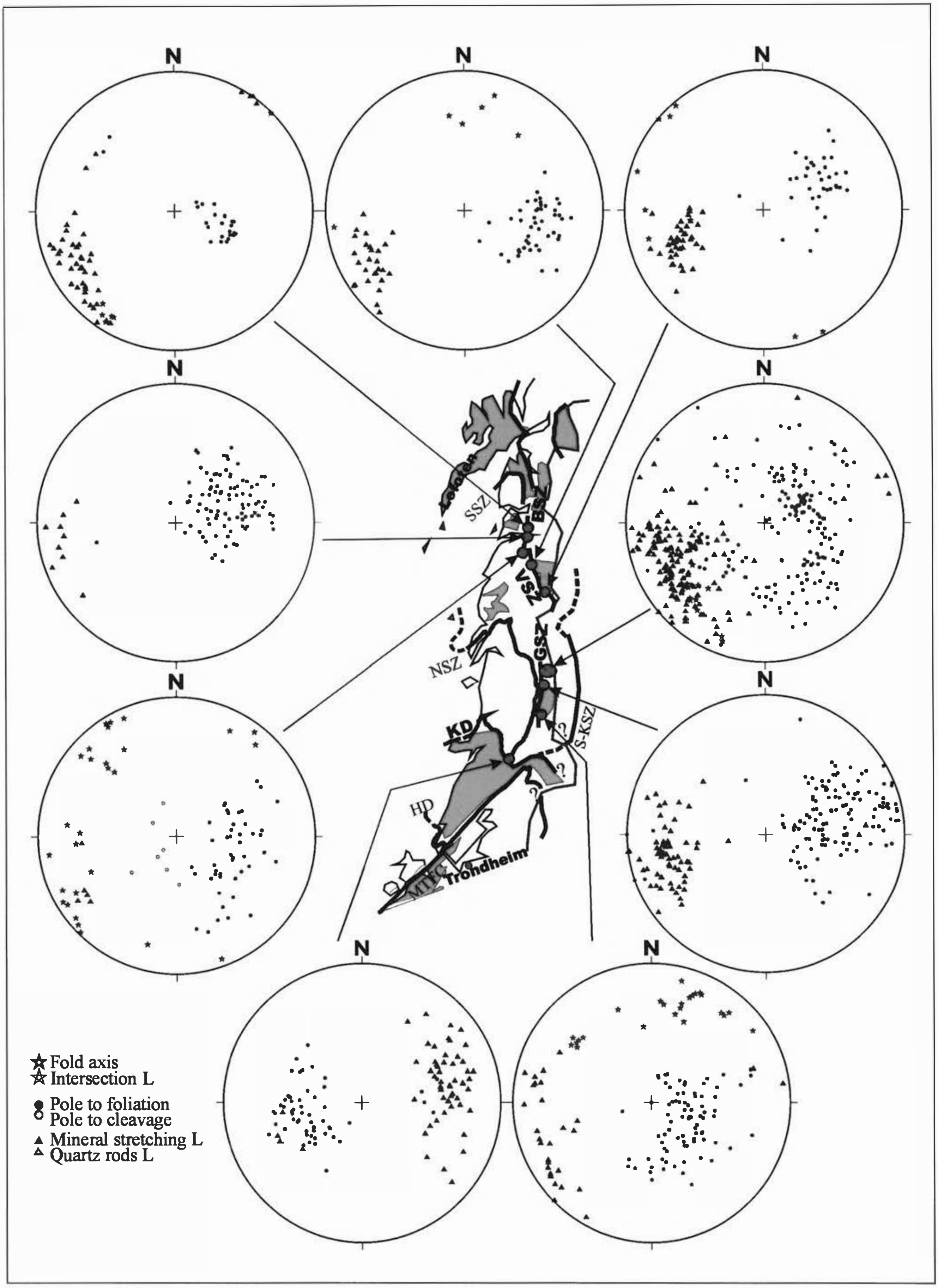

Fig. 8. Structural data from low-grade extensional shear zones. Areas for data acquisition are approximately located.

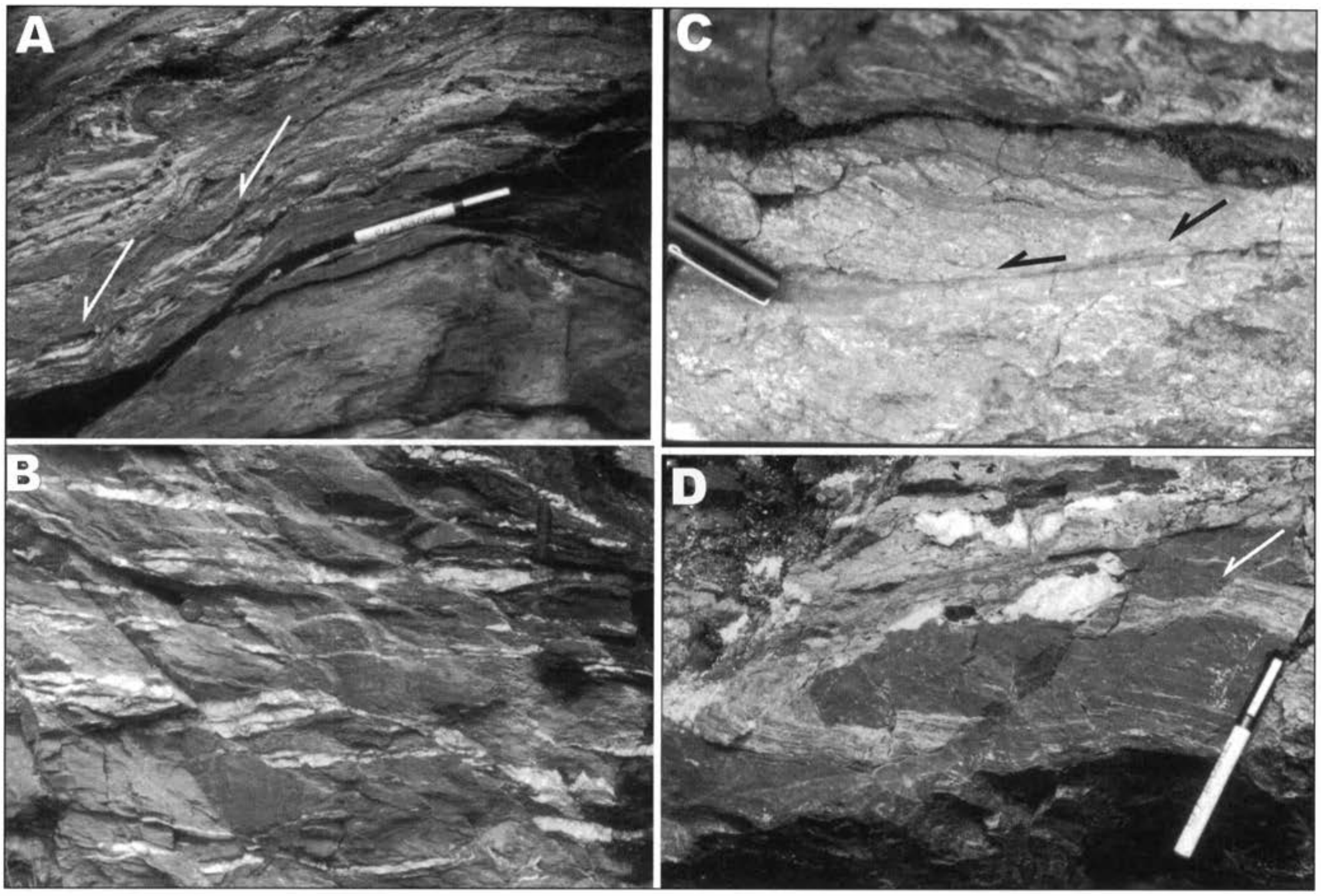

Fig. 9. Examples of structures in low-grade shear and fault zones. (a) Normal, top-WSW shear bands in mylonitic marble of the Gaukarelv shear zone in Hattfjelldal, seen from the south. UTM(33) 453738-7275497. (b) Semi-brittle shear bands and faults along the southeastern portion of the Kollstraumen detachment. These shear bands truncate the southern extension of the Nesna shear zone. View is towards the west. UTM(32) 359300-7277600. (c) Top-WSW semi-brittle shear fabric, consisting of foliated cataclasite and bands of ultracataclasite, found along parts of the Gaukarelv shear zone; view towards northwest. UTM 444100-7219950. (d) Late, top-SW faults that truncate the folded, mylonitic fabric of the Gaukarelv shear zone; looking west. UTM 444100-7219950.

dian thrusting event; (ii) syn-extensional dyke intrusion ended at around 398 Ma when most, if not all, medium-grade shear zones were active; and (iii) major extension continued into Late Devonian- Early Carboniferous time.

Key observations for this evolution include U-Pb zircon ages from syn-extensional felsic dykes (KD and the CNBW culmination; basement of footwall to NSZ), which range in age between 420 Ma and 398 Ma, with the majority around 400 Ma (Schouenborg 1988; Schouenborg et al. 1991; Dallmeyer et al. 1992; Larsen et al. 2002; Nordgulen et al. 2002). This time-span overlaps with the evolution established for the southwestern part of the MTFC, in the Møre region, where Terry et al. (2000a, b) reported rapid thrust-related ascent of ultra-high pressure, eclogitic lower crust between 407 Ma and 395 Ma, followed by slower extension-related unroofing until 375 Ma. Likewise, a U-Pb titanite age of 395 Ma from the Nasafjäll basement window (Essex & Gromet 2000) most likely dates the activity on the medium-grade Randal shear zone (Osmundsen et al. 2003). Rb-Sr and Ar-Ar geochronology from the CNBW and from bounding faults and shear zones falls in the range 410-385 Ma (e.g., Piasecki & Cliff 1988; Dallmeyer et al. 1992; Watts et al. 2001), which suggests a temporal link to activity along the Nesna shear zone. There, syn-tectonic micas bracket the shear-zone activity to between 397 and 387 Ma (Eide et al. 2002), whereas ^{40}Ar-^{39}Ar ages of the footwall windows (amphibole of 418-401 Ma, Dallmeyer 1988; biotite of 390-378 Ma, Eide et al. 2002) are slightly younger, in accordance with an expected uplift/cooling gradient. Younger activity is documented by a U-Pb titanite age of 368 Ma from a cataclastic fault zone (Træna; Larsen et al. 2002), various Rb-Sr and ^{40}Ar-^{39}Ar ages between 380 and 350 Ma (Wilson & Nicholson 1973; Wilberg 1987), and K-feldspar blocking ages near 340 Ma (Eide et al. 2002); all these locations are in a northern, footwall position of the Nesna shear zone. Farther north, Coates et al. (1999; see also Andresen & Tull 1986) have reported Late Devonian-Early Carboniferous ages (371-355 Ma) from ductile-to-brittle, top-W, extensional shear zones along the western flank of the Rombak basement window (Fig. 1b).

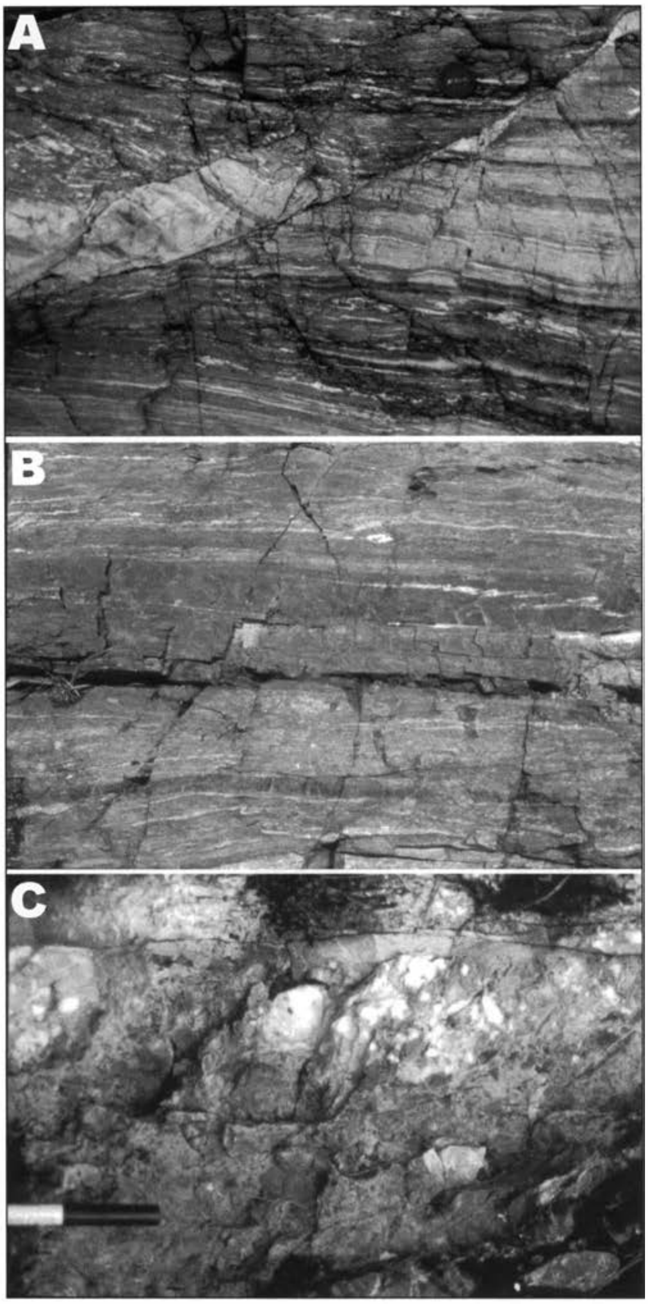

Figure 10. Examples of late, brittle faults that reactivate the older shear zones. (a) Listric, normal faults that rejuvenate the mylonitic fabric of the Høybakken detachment; view towards northwest. UTM(32) 535385-7082700. (b) Dark grey to blackish, c. 1 m-wide ultramylonite zone, revealing top-ENE shear, as indicated by folds and imbricates within the shear zone. View towards north. Several such zones are present within the Nesna shear zone. Their kinematic pattern is consistent with thrust faulting and kink-folding in other parts of the shear zone. UTM 405840-7340290. (c) Zeolite-cemented breccia from the southern part of the Helgeland Nappe Complex. The breccia contains fragments of greenish cataclasite and other zeolite breccias, showing the long-lived nature of the fault zone. This fault zone has a listric geometry, and probably roots in marbles of the Kollstraumen detachment. UTM(32) 375573-7206281.

Orogen-parallel, extensional denudation

Devonian extensional denudation of the Caledonides in Central and northern Central Norway can be depicted by two overall temporal phases (Fig. 12), on the basis of the crustal position of extensional shear zones during their formation (metamorphic grade), and on their structural characteristics and truncating nature (involvement of Fennoscandian basement). In the Early Devonian, medium-grade, low-angle and top-WSW (locally top-ENE) shear zones sliced through and extended the Caledonian nappe pile. Deformation occurred above Fennoscandian basement and was rooted in a fundamental sole zone in the middle crust, a décollement, which probably coincides with the Scandian basal thrust zone. Reconstruction of the region suggests that a steep, orogen-parallel, strike-slip fault zone, the proto-MTFC, linked several of the major extensional shear zones. Synchronous extension and extension-parallel folding during this period is consistent with ongoing compression or transpression, which could relate to the terminal stages of collision between Baltica and Laurentia. NW-SE contraction, most pronounced in the middle crust (e.g., CNBW), interacted with bulk WSW-ENE, middle-crustal stretching. In the upper-crustal supradetachment rocks (e.g., HNC of Fig. 2), continued contraction and near orogen-parallel extension were expressed by conjugate, mainly brittle faults that allowed this crustal segment to escape parallel to the orogen. This mechanism also accommodates formation of the Early Devonian supradetachment basins. On a broader scale, such crustal response in many ways resembles recent tectonism in the Himalayas (Andersen & Jamtveit 1990; Andersen et al. 2002), where thrusting at deep levels is complemented by upper-crustal extension and escape block tectonics (e.g., Le Pichon et al. 1992).

For Mid-Late Devonian to Early Carboniferous time, our data indicate continued activity on several of the older detachments, as well as formation of new, low-grade shear zones (BSZ, VSZ and GSZ; Figs. 2 and 3). These shear zones cut deeper, i.e. through raised, structural levels of the medium-grade shear zones, as is clearly seen by involvement of parautochthonous(?) Fennoscandian basement. Besides, local truncation of medium-grade detachments, such as the southern Nesna shear zone, by the low-grade shearing along the Kollstraumen detachment, demonstrates a structural chronology. Overall geometries of low-grade shear zones are mainly consistent with sinistral-normal shearing, e.g., related to the development of steep faults within the sinistral Møre-Trøndelag Fault Complex (e.g., Grønlie et al. 1994; Watts et al. 2001), as suggested by linking fault strands between this fault complex and the Gaukarelv shear zone north of the Grong-Olden culmination (Roberts 1998). Open, regional folds that deve-

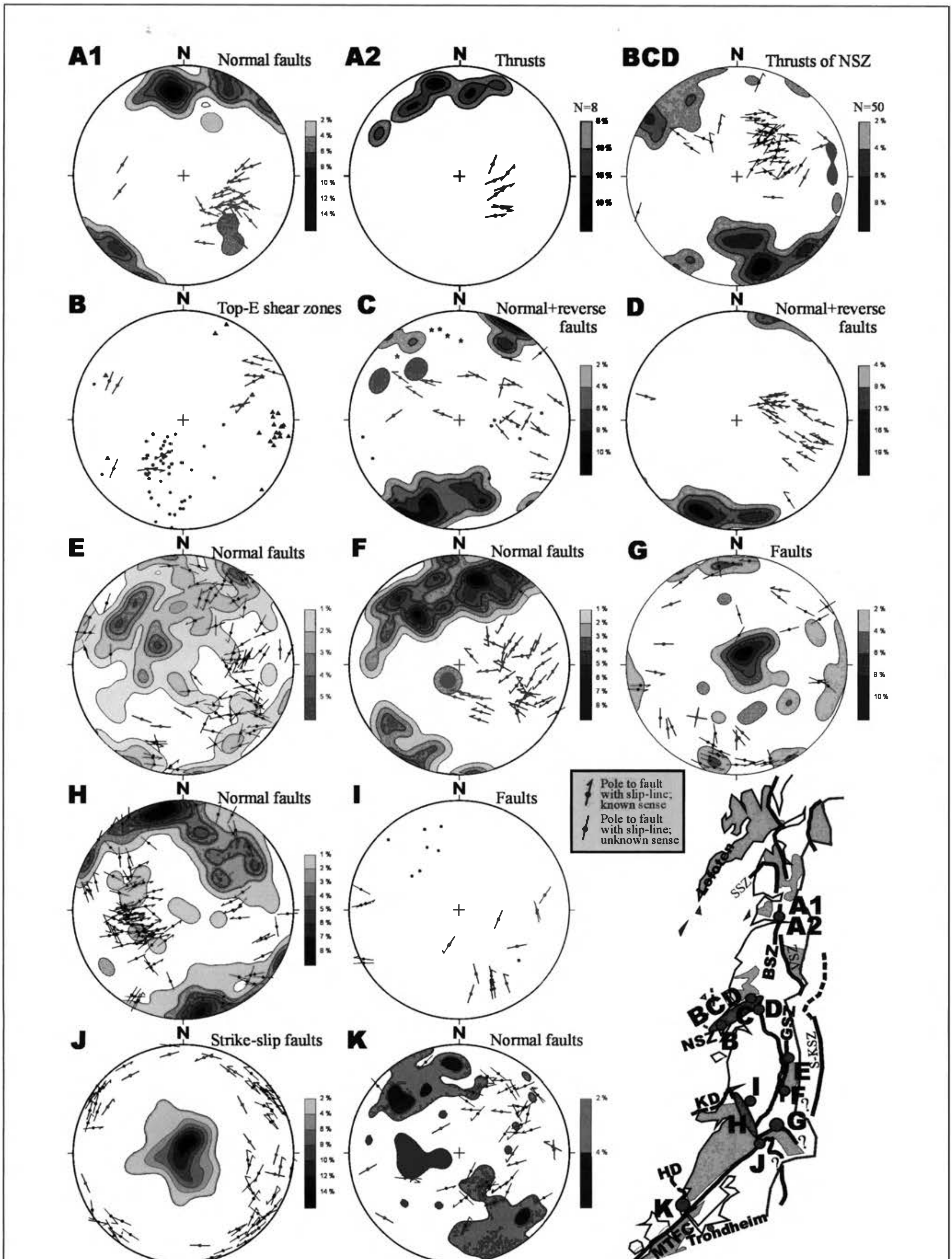

Fig. 11. Structural data of brittle fault systems, displaying slip-linear information and contoured poles to movement planes (M-planes). Areas for data acquisition are approximately located. See caption to Figure 5 for plotting method.

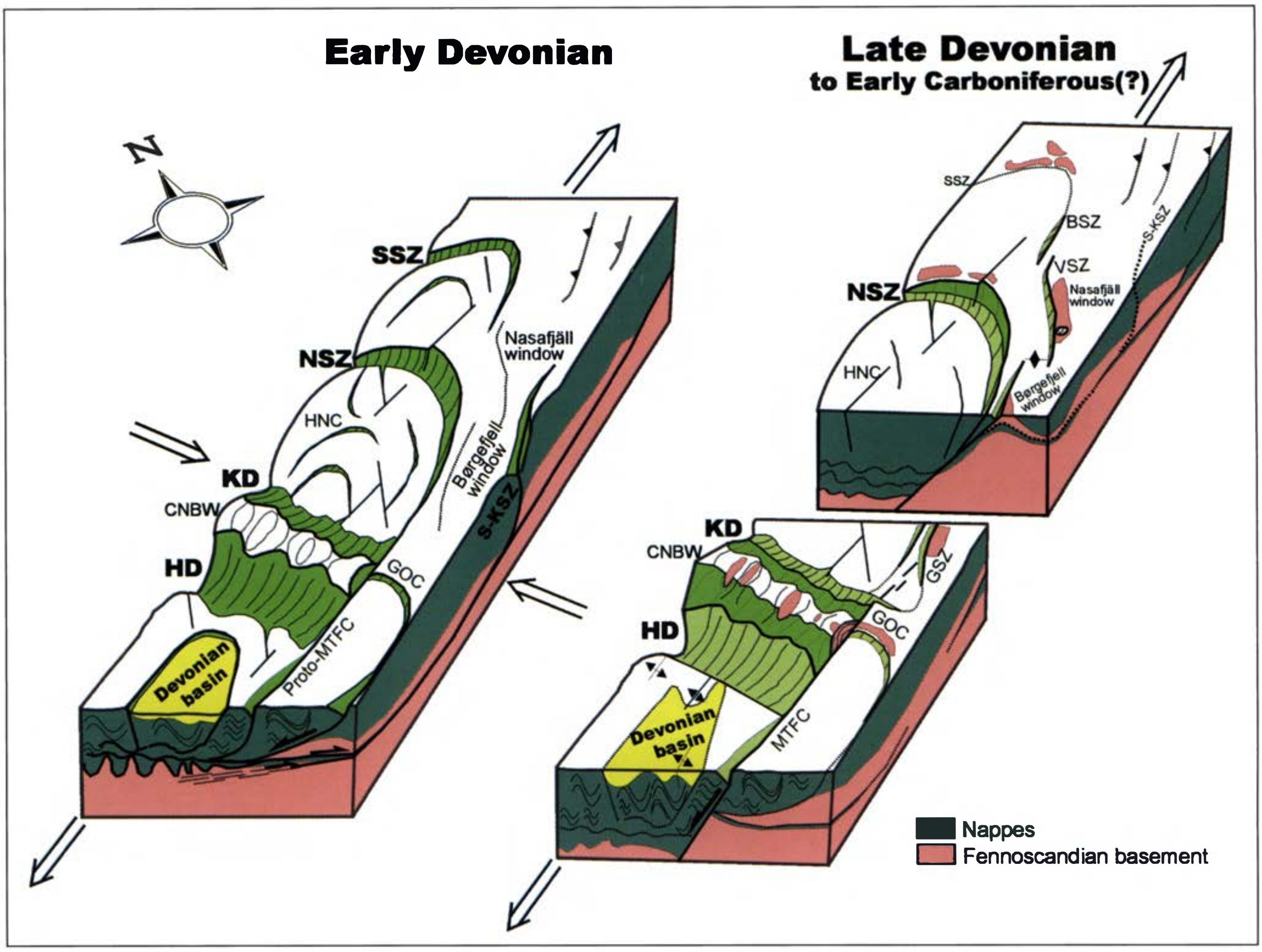

Fig. 12. Schematic reconstructions of the Devonian template for the Central and northern Central Norwegian province, showing the orogen-parallel extensional denudation of the Scandian orogen. Abbreviations are as shown in Figure 2.

loped during this time interval, and seen as elongated basement culminations subparallel to the shear zones, are most easily explained through passive folding during unroofing. This is consistent with a shift from the Early Devonian mild contraction and near orogen-parallel extension, to a Mid-Late Devonian setting dominated by sinistral transtension.

The general consensus on Scandian thrust directions in Central and north Central Norway and western Central Sweden, is that transport was approximately to the SE (e.g., Roberts & Gee 1985; Stephens et al. 1985; Milnes et al. 1987), as documented by, e.g., Hossack (1968), Morley (1987), Townsend (1987), Fossen (1993), Greiling et al (1993), and Bergman & Sjöström (1997). In any case, an overall 070-250° stretching axis is not truly perpendicular to SE-directed (c. 135°) nappe emplacement. If latest-Scandian contraction and hinterland extension coincided, these structural styles were decoupled, which mimics the latest-Caledonian pattern of western Norway (Andersen & Jamtveit 1990; Andersen 1998). There, two crustal layers are depicted; (i) a lower crust (lower plate) characterised by horizontal shortening followed by vertical flattening, and (ii) a middle-upper crust (upper plate) truncated by extensional detachment(s) with associated supradetachment faults. In North Norway, a similar two-layer crustal setting has been suggested by Northrup & Burchfiel (1996). They describe mutual, orogen-normal and orogen-parallel thrusting in partitioned upper and middle crust, respectively, and apply this to sinistral transpression at a late stage of the orogenic collision. This has applications to northern Central Norway, where strain partitioning likely occurred within the middle crust, i.e. along the sole detachment zone to the medium-grade extensional shear zones. Below this structure, thrusting/contraction prevailed, as suggested for the Møre region (Terry et al. 2000a, b). Above the sole detachment, extension dominated, albeit extension-parallel, open folds may mirror minor contraction. Within the detachment zone itself, strain was complex, with combined folding and extension-related shear, the latter of which could have led to fold decapitation. In this light, the proto-MTFC strike-slip zone (Fig. 12) is consistent with a fundamental strain-partitioning structure of the middle and upper crust, i.e., above the sole detachment.

It may have separated a western, extension-dominated domain in the middle-upper crust from an eastern, mainly contractional domain that formed in response to contraction of the lower crust farther west. In southern Norway, a temporal link between latest-Caledonian extension and thrust imbrication of foreland deposits suggests that extension and contraction interacted (e.g., Andersen 1998), which may well be an analogue to northern Central Norway.

The cause of the current structural position of the basement culminations in the Caledonides is still disputed (Braathen et al. 2001; Rice 2001a). It is argued that several gneiss-cored windows relate to imbricate stacks or duplexes, e.g. in Finnmark (Gayer et al. 1987; Rice 2001b) or at Børgefjell (Greiling et al. 1998). This may well be so, especially east of the extensional province, such as in Finnmark. However, thrusting cannot account for juxtaposed parautochthonous(?) basement and uppermost Caledonian nappe units, a structural relationship commonly seen associated with extension (e.g., Andersen et al. 1999; Osmundsen et al. submitted) or, alternatively, but not relevant in this case, with major out-of-sequence thrusting. From a strict geometrical point of view, low-angle thrusting (commonly « 10°) does not contribute to any significant uplift of rocks in comparison to high-angle extensional shear zones, even though the net slip may be of different orders (e.g., Platt 1993). From Børgefjell, it is clear that both thrusting and extension may have contributed to the basement culminations. However, geophysical modelling (Sindre 1998) suggests that the extensional Gaukarelv shear zone displaces the basement-cover contact in a down-west fashion with an offset in the range of 3-6 km. Since the Børgefjell basement window appears as a footwall culmination of this shear zone, it is most reasonable that extension played a key role in the unroofing of this window.

At the scale of the Scandinavian Caledonides, there is a striking change in the latest-Caledonian extensional transport direction. In western Norway, E-W extension gradually changes northwards (e.g., Roberts 1983; Osmundsen & Andersen 2001), to a NE-SW trend in proximity to the Møre-Trøndelag Fault Complex (Séranne 1992, Braathen et al. 2000). Farther north, this approximately NE-SW stretching axis, highly oblique to the orogen, persists for 600 km through northern Central Norway, before becoming approximately E-W again in northern Norway (Rykkelid & Andresen 1994; Klein et al. 1999). On the orogenic scale, such shifts in the extensional system suggest that lateral movements played a critical role in the terminal stages of Caledonian evolution.

A bimodal structural pattern is depicted for the latest-Scandian extension (e.g., Fossen 2000), as follows; (i) Broad, normal-slip detachment zones, influencing larger provinces; these are present in West (e.g., Andersen 1998; Fossen 2000) and Central Norway (Braathen et al. 2000; Osmundsen et al. 2003), and in East Greenland (e.g., Hartz et al. 2000); (ii) major, rather narrow sinistral strike-slip shear zones, some of which were important terrane boundaries; these include the Great Glen, Walls Boundary and Highland Border Fault Zones (e.g., Stewart & Strachan 1999; Stewart et al. 2001), and the Møre-Trøndelag Fault Complex (e.g., Grønlie & Roberts 1989; Grønlie et al. 1991). The overall process probably reflects a combination of oblique plate collision, crustal thickening, complex orogenic collapse with significant lateral movements, and localised, regenerated vertical movement.

Acknowledgements: - We thank the following BAT project sponsors for their strong support during the past five years: Norsk Agip, BP, ChevronTexaco, ConocoPhillips, ExxonMobil, Norsk Hydro ASA, Norske Shell, and Statoil. Research affiliations and exchanges with the Norwegian Petroleum Directorate and the University of Oslo have also been of benefit to the project. We are grateful to T.B. Andersen, S.G. Bergh, and R. Greiling who contributed with constructive reviews.

References

Andersen, T. B. 1998: Extensional tectonics in the Caledonides of southern Norway, an overview: *Tectonophysics 285*, 333-351.

Andersen, T.B, Hartz, E., Torsvik, T.H., Osmundsen, P.T., Andresen, A., Eide, E.A. & Braathen, A. 2002: The aftermath of the Caledonian continental collision in the North Atlantic Region: A structural template for later events? *Abstracts and Proceedings of the Norwegian Geological Society 2*, 12-14.

Andersen, T.B. & Jamtveit, B. 1990: Uplift of deep crust during orogenic extensional collapse: A model based on field studies in the Sogn-Sunnfjord region of Western Norway. *Tectonics 9*, 1097-1111.

Andersen, T.B., Osmundsen, P.T. & Jolivet, L. 1994: Deep crustal fabrics and a model for the extensional collapse of the southwest Norwegian Caledonides. *Journal of Structural Geology 16*, 1191-1203.

Andersen, T.B., Torsvik, T.H., Eide, E.A., Osmundsen, P.T. & Faleide, J.I. 1999: Permian and Mesozoic extensional faulting within the Caledonides of central South Norway. *Journal of the Geological Society, London 156*, 1073-1080.

Andresen, A. & Tull, J.F. 1986: Age and tectonic setting of the Tysfjord gneiss granite, Efjord, North Norway. *Norsk Geologisk Tidsskrift 66*, 69-80.

Bergmann, S. & Sjöström, H. 1997: Accretion and lateral extension in an orogenic wedge: evidence from a segment of the Seve-Köli terrane boundary, central Scandinavian Caledonides. *Journal of Structural Geology 19*, 1073-1091.

Braathen, A. 1999: Kinematics of polyphase brittle faulting in the Sunnfjord region, western Norway: *Tectonophysics 302*, 99-121.

Braathen, A., Nordgulen, Ø., Osmundsen, P.T., Andersen, T.B., Solli, A. & Roberts, D. 2000: Devonian, orogen-parallel, opposed extension of the Central Norway Caledonides. *Geology 28*, 615-618.

Braathen, A., Nordgulen, Ø., Osmundsen, P.T., Andersen, T.B., Solli, A. & Roberts, D. 2001: Devonian, orogen-parallel, opposed extension of the Central Norway Caledonides: Reply. *Geology 29*, 375-376.

Coates, B.H., Zeltner, D.L., Carter, B.T., Steltenpohl, M.G., Andresen, A. & Kunk. M.J. 1999: $^{40}Ar/^{39}Ar$ and structural investigations of extensional development of the North-Central Norwegian margin. *Geological Society of America Abstracts with programs 31*, p. 118.

Dallmayer, R.D. 1988: Polyphase tectonothermal evolution of the Scandinavian Caledonides. In Harris, A.L. & Fettes, D.J. (eds.), *The Caledonian-Appalachian Orogen*, 365-379. Geological Society Special Publication 38.

Dallmeyer, R.D., Johansson, L. & Møller, C. 1992: Chronology of Caledonian high-pressure granulite-facies metamorphism, uplift, and deformation within northern parts of the Western Gneiss Region. *Geological Society of America Bulletin 104*, 444-455.

Eide, E.A., Osmundsen P.T., Meyer, G.B., Kendrick, M.A. & Corfu, F. 2002: The Nesna Shear Zone, north-central Norway: an $^{40}Ar/^{39}Ar$ record of Early Devonian – Early Carboniferous ductile extension and unroofing. *Norwegian Journal of Geology 82*, 317-339.

Eide, E. A., Torsvik, T. H. & Andersen, T. B. 1997: Absolute dating of brittle fault movements: Late Permian and late Jurassic extensional fault breccias in western Norway: *Terra Nova 9*, 135-139.

Eide, E.A., Torsvik, T.H., Andersen, T.B. & Arnaud N.O. 1999: Early Carboniferous Unroofing in Western Norway: A Tale of Alkali Feldspar Thermochronology. *Journal of Geology 107*, 353-374.

Engvik, A.K. & Andersen, T.B. 2000: Evolution of Caledonian deformation fabrics under eclogite and amphibolite facies at Vårdalsneset, Western Gneiss Region, Norway. *Journal of Metamorphic Geology 18*, 241-257.

Erambert, M. & Braathen, A. in press. Structural and metamorphic evolution during exhumation of the Engebøfjellet eclogite, Western Gneiss Region, Norway. *Journal of Metamorphic Petrology.*

Essex, R.M. & Gromet, L.P. 2000: U-Pb dating of prograde and retrograde titanite growth during the Scandian orogeny. *Geology 28*, 419-422.

Fossen, H. 1993: Linear fabrics in the Bergsdalen Nappes, southwest Norway: implications for deformation history and fold development. *Norsk Geologisk Tidsskrift 73*, 95-108.

Fossen, H. 1992: The role of extensional tectonics in the Caledonides of southern Norway. *Journal of Structural Geology 14*, 1033-1046.

Fossen, H. 2000: Extensional tectonics in the Caledonides: Synorogenic or postorogenic? *Tectonics 19*, 213-224.

Gabrielsen, R.H., Odinsen, T. & Grunnaleite, I. 1999: Structuring of the Northern Viking Graben and the Møre Basin; the influence of basement structural grain, and the particular role of the Møre-Trøndelag Fault Complex. *Marine and Petroleum Geology 16*, 443-465.

Gayer, R.A., Rice, A.N.N., Roberts, D., Townsend, C. & Welbon, A. 1987: Restoration of the Caledonian Baltoscandian margin from balanced cross-sections; the problem of excess continental crust. *Transactions of the Royal Society of Edinburgh, Earth Sciences 78*, 197-217.

Gee, D.G & Sturt, B.A. (editors) 1985: *The Caledonian Orogeny - Scandinavia and related areas.* John Wiley & Sons.

Goldstein, A. & Marshak, S. 1988: Analysis of fracture array geometry. *In* Marshak, S. & Mitra, G. (eds.), *Basic Methods of Structural Geology*, p. 249-268, Prentice-Hall, Eaglewood Cliffs, New Jersey.

Greiling, R.O., Garfunkel, Z. & Zachariasson, E. 1998: The orogenic wedge in the central Scandinavian Caledonides: Scandian structural evolution and possible influence on the foreland basin. *Geologiska Föreningens i Stockholm, Förhandlingar 120*, 181-190.

Greiling, R.O., Geyer, R.A. & Stephens, M.B. 1993: A basement culmination in the Scandinavian Caledonides formed by antiformal stacking (Bangonaive, northern Sweden). *Geological Magazine 130*, 471-482.

Grønlie, A., Naeser, C.W., Naeser, N.D., Mitchell, J.G., Sturt, B.A. & Ineson, P.R. 1994: Fission-track and K-Ar dating of tectonic activity in a transect across the Møre-Trøndelag Fault Zone, central Norway. *Norsk Geologisk Tidsskrift 74*, 24-34.

Grønlie, A. & Roberts, D. 1989: Resurgent strike-slip duplex development along the Hitra-Snåsa and Verran Faults, Møre-Trøndelag Fault Zone, Central Norway: *Journal of Structural Geology 11*, 295-305.

Grønlie, A., Nilsen, B. & Roberts, D. 1991: Brittle deformation history of fault rocks on the Fosen Peninsula, Trøndelag, Central Norway. *Norges geologiske undersøkelse Bulletin 421*, 39-57.

Gustavson, M. & Gjelle, S.T. 1991: Map-sheet Mo i Rana, 1:250 000. *Norges geologiske undersøkelse.*

Hartz, E., Andresen, A., Martin, M.W. & Hodges, K.V. 2000: U-Pb and $^{40}Ar/^{39}Ar$ constraints on the Fjord Region Detachment Zone: a long-lived extensional fault in the East Greenland Caledonides. *Journal of the Geological Society, London 157*, 795-809.

Hossack, J.R. 1968: Structural history of the Bygdin area, Oppland. *Norges geologiske undersøkelse 247*, 78-107.

Hossack J.R. 1984: The geometry of listric growth-faults in the Devonian basins of Sunnfjord, West Norway. *Journal of the Geological Society, London 141*, 629-638.

Hurich, C.A., Palm, P., Dyerlius, D., Kristoffersen, Y., Wolff, F.C. & Roberts, D. 1988: Activation of Precambrian basement in the Scandinavian Caledonides: View from seismic reflection data. *Norges geologiske undersøkelse Special Publication 3*, 66-69.

Hurich, C.A. & Roberts, D. 1997: A seismic reflection profile from Stjørdalen to Outer Fosen, Central Norway: a note on the principal results. *Norges geologiske undersøkelse Bulletin 433*, 18-19.

Ihlen, P.M. 1993: Gold mineralisation in relation to batholith magmatism in the Helgeland Nappe Complex and its immediate substrata, the Caledonides of north-central Norway. *Geological Survey of Greenland Open File Series 95/10*, 42-46.

Klein, A.C., Steltenpohl, M.G., Hames, W.E. & Andresen, A. 1999: Ductile and brittle extension in the southern Lofoten archipelago, north Norway: Implications for differences in tectonic style along an acient collision margin. *American Journal of Science 299*, 69-89.

Krabbendam, M. & Dewey, J.F. 1998: Exhumation of UHP rocks by transtension in the Western Gneiss Region, Scandinavian Caledonides. *Geological Society of London Special Publication 135*, 159-181.

Larsen, Ø., Skår, Ø. & Pedersen, R.B. 2002: U-Pb zircon and titanite geochronological constraints on the late- to post-Caledonian basement evolution of the Scandinavian Caledonides in Central Nordland, northern Norway. *Norwegian Journal of Geology 82*, 1-14.

Le Pichon, X., Fournier, M. & Jolivet, L. 1992: Kinematics, topography, shortening, and extrusion in the India-Eurasia collision. *Tectonics 11*, 1085-1098.

Lindquist, J.E. 1990: Thrust-related metamorphism in basement windows of the central Scandian Caledonides. *Journal of the Geological Society, London 147*, 69-80.

Lister, G.S. & Davis, G.A. 1989: The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in northern Colorado River region, U.S.A. *Journal of Structural Geology 11*, 65-94.

Morley, C.K. 1987: Lateral and vertical changes of deformation style in the Osen-Røa thrust sheet, Oslo region. *Journal of Structural Geology 9*, 331-343.

Milnes, A.G., Wennberg, O.P., Skår, Ø. & Koestler, A.G. 1997: Contraction, extension and timing in the South Norwegian caledonides: The Sognefjord transect. *Geological Society of London Special Publication 121*, 123-148.

Möller, C. 1988: Geology and metamorphic evolution of the Roan area, Vestranden Western Gneiss Region, Central Norwegian Caledonides. *Norges geologiske undersøkelse Bulletin 413*, 1-31.

Nordgulen, Ø., Bickford, M. E., Nissen, A. L. & Wortman, G. L. 1993: U-Pb zircon ages from the Bindal Batholith, and the tectonic history of the Helgeland Nappe Complex, Scandinavian Caledonides: *Journal of the Geological Society, London 150*, 771-783.

Nordgulen, Ø., Braathen, A., Corfu, F. & Osmundsen, P.T. 2002: Polyphase kinematics and geochronology of the Kollstraumen detachment. *Norwegian Journal of Geology 82*, 299-316.

Northrup, C.J. & Burchfiel, B.C. 1996: Orogen-parallel transport and vertical partitioning of strain during oblique collision, Efjorden, north Norway. *Journal of Structural Geology 18*, 1231-1244.

Norton, M. 1986: Late Caledonian extension in western Norway: A response to extreme crustal thickening. *Tectonics 5*, 195-204.

Olesen, O., Lundin, E., Nordgulen, Ø., Osmundsen, P.T., Skilbrei, J.R., Smethurst, M.A., Solli, A., Bugge, T. & Fichler, C. 2002: Bridging the gap between the onshore and offshore geology in Nordland, northern Norway. *Norwegian Journal of Geology 82*, 243-262.

Osmundsen, P.T. & Andersen, T.B. 2001: The middle Devonian basins of western Norway: sedimentary response to large-scale transtensional tectonics? *Tectonophysics 332*, 51-68.

Osmundsen, P. T., Andersen, T. B., Markussen, S. & Svendby, A.K. 1998: Tectonics and sedimentation in the hanging wall of a major extensional detachment: The Devonian Kvamshesten basin, western Norway. *Basin Research 10*, 213-234.

Osmundsen, P.T., Braathen, A., Nordgulen, Ø., Roberts, D., Meyer, G.B. & Eide, E. 2003: Late/post Caledonian extension in North-Central Norway: The Nesna shear zone and its regional implications. *Journal of the Geological Society, London 160*, 1-14.

Osmundsen, P.T., Braathen, A., Sommaruga, A., Eide, E., Skilbrei, J.R., Olesen, O., Nordgulen, Ø. Roberts, D., Andersen, T.B. & Mosar, J. submitted: Metamorphic core complexes and gneiss-cored culminations along the Mid-Norwegian margin: an overview and some current ideas. Norwegian Petroleum Society Special Publication.

Osmundsen, P.T., Sommaruga, A., Skilbrei, J.R. & Olesen, O. 2002: Deep structure of the Mid Norway passive margin. *Norwegian Journal of Geology 82*, 205-224.

Platt, J.P. 1993: Exhumation of high-pressure rocks: a review of concepts and processes. *Terra Nova 5*, 119-133.

Piasecki, M. A. J. & Cliff, R. A. 1988: Rb-Sr dating of strain-induced mineral growth in two ductile shear zones in the Western Gneiss Region of Nord-Trøndelag, Central Norway. *Norges geologiske undersøkelse Bulletin 413*, 33-50.

Pichon, X., Fournier, M. & Jolivet, L. 1992: Kinematics, topography, shortening, and extrusion in the India-Eurasia collision. *Tectonics 11*, 1085-1098.

Rice, A.H.N. 2001a: Devonian, orogen-parallel, opposed extension of the Central Norway Caledonides: Comment. *Geology 29*, 373-374.

Rice, A.H.N. 2001b: Field evidence for thrusting of the basement rocks coring tectonic windows in the Scandinavian Caledonides; an insight from the Kunes Nappe, Finnmark, Norway. *Norsk Geologisk Tidsskrift 81*, 321-328.

Roberts, D. 1983: Devonian tectonic deformation in the Norwegian Caledonides and its regional perspective. *Norges geologiske undersøkelse 380*, 85-96.

Roberts, D. 1998: Geology of the Fosen Peninsula and Trondheimsfjord Region: a synopsis and excursion guide: *Norges geologiske undersøkelse Report 98*.119, 38 pp.

Roberts, D. & Gee, D.G. 1985: An introduction to the Scandinavian Caledonides. *In* Gee, D.G. & Sturt, B.A. (eds.), *The Caledonian Orogeny - Scandinavia and related areas*, 55-68. John Wiley & Sons.

Robinson, P. 1995: Extension of Trollheimen tectono-stratigraphic sequence in deep synclines near Molde and Brattvåg, Western Gneiss Region, southern Norway. *Norsk Geologisk Tidsskrift 75*, 181-198.

Rykkelid, E. & Andresen, A. 1994: Late Caledonian extension in the Ofoten area, northern Norway. *Tectonophysics 231*, 157-169.

Schouenborg, B. 1988: U/Pb-zircon datings of Caledonian cover rocks and cover-basement contacts, northern Vestranden, central Norway. *Norsk Geologisk Tidsskrift 68*, 75-87.

Schouenborg, B., Johansson, L. & Gorbatschev, R. 1991: U-Pb zircon ages of basement gneisses and discordant felsic dykes from Vestranden, westernmost Baltic shield and central Norwegian Caledonides. *Geologische Rundschau 80*, 121-134.

Séranne, M. 1992: Late Palaeozoic kinematics of the Møre-Trøndelag Fault Zone and adjacent areas, central Norway. *Norsk Geologisk Tidsskrift 72*, 141-158.

Sindre, A. 1998. Tolkning av dyp til basement under de kaledonske dekkebergartene i Nordland fra gravimetriske data. *Norges geologiske undersøkelse Report 97*.179, 24 pp.

Skilbrei, J.R., Olesen, O., Osmundsen, P. T., Kihle, O., Aaro, S. & Fjellanger, E. 2002: A study of basement structures and some onshore-offshore correlations in Central Norway. *Norwegian Journal of Geology (NGT) 82*, 263-279.

Stephens, M.B., Gustavson M., Ramberg, I.B. & Zachrisson, E. 1985: The Caledonides of central-north Scandinavia – a tectonostratigraphic overview. *In* Gee, D.G. & Sturt, B.A. (eds.), *The Caledonian Orogeny - Scandinavia and related areas*, 135-163. John Wiley & Sons.

Stewart, M. & Strachan, R.A. 1999: Structure and early kinematic history of the Great Glen Fault Zone, Scotland. *Tectonics 18*, 326-342.

Stewart, M., Strachan, R.A., Martin, M.W. & Holdsworth, R.E. 2001: Constraints on early sinistral displacement along the Great Glen Fault Zone, Scotland: structural setting, U-Pb geochronology and emplacement of the syn-tectonic Clunes tonalite. *Journal of the Geological Society, London 158*, 821-830.

Sturt, B.A. & Braathen, A. 2001: Deformation and metamorphism of Devonian rocks in the outer Solund area, western Norway – implications for models of Devonian deformation. *International Journal of Earth Sciences (Geologische Rundschau) 90*, 270-286.

Terry, M.P., Robinson, P., Hamilton, M.A. & Jercinovic, M.J. 2000a: Kyanite eclogite thermobarometry and evidence for thrusting of UHP over HP metamorphic rocks, Nordøyane, Western Gneiss Region, Norway. *American Mineralogist 85*, 1637-1650.

Terry, M.P., Robinson, P., Hamilton, M.A. & Jercinovic, M.J. 2000b: Monazite geochronology of UHP and HP metamorphism, deformation and exhumation, Nordøyane, Western Gneiss Region, Norway. *American Mineralogist 85*, 1651-1664.

Thelander, T., Bakker, E. & Nicholson, R. 1980: Basement-cover relationships in the Nasafjället Window, central Swedish Caledonides. *Geologiska Föreningens i Stockholm Förhandligar 102*, 569-580.

Torsvik, T.H., Sturt, B.A., Swensson, E., Andersen, T.B. & Dewey, J.F. 1992: Paleomagnetic dating of fault rocks: evidence for Permian and Mesozoic movements and brittle deformation along the extensional Dalsfjorden Fault, western Norway. *Geophysics Journal International 109*, 565-580.

Townsend, C. 1987: Thrust transport directions and thrust sheet restoration in the Caledonides of Finnmark, North Norway. *Journal of Structural Geology 9*, 345-352.

Watts, L.M. 2002: The Walls Boundary Fault Zone and the Møre-Trøndelag Fault Complex: a case study of two reactivated fault zones. PhD thesis, University of Durham, 550 pp.

Watts, L.M., Sherlock, S., Holdsworth, R.E. & Roberts, D. 2001: Regional implications of Ar39-Ar40 pseudotachylite ages from the reactivated Møre-Trøndelag Fault Complex, Central Norway (Abstract). *Tectonics Study Group Meeting, University of Leeds, January 2001*, Abstract volume.

Wernicke, B. 1985: Uniform sense normal simple shear of the continental lithosphere. *Canadian Journal of Earth Sciences 22*, 108-125.

Wilberg, R. 1987: Rekognoserende Rb-Sr aldersbestemmelser av granitisk gneiser fra grunnfjellsvinduene Høgtuva og Sjona I Nordland. *Norges geologiske undersøkelse rapport 87.074*, 21 pp.

Wilson, M.R. & Nicholson, R. 1973: The structural setting and geochronology of basal granitic gneisses in the Caledonides of parts of Nordland, Norway. *Journal of the Geological Society, London 129*, 365-387.