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High-strain zones from meso- to macro-scale at different structural levels, Central Norwegian Caledonides

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Abstract—High-strain shear zones of diverse character, metamorphic grade and scale occur in different tectonic settings in the Caledonides of Central Norway. Three specific examples are described. Strain products range from high-PT granulite to amphibolite-facies, thrust-related, Scandian mylonites at deep structural levels, to ultracataclasites and mylonites generated in the ductile to ductile–brittle transition regimes along the multiply reactivated, orogen-oblique Møre–Trøndelag Fault Complex. In another example, geochemical data from a transformation of granite to mylonite at an intermediate structural level indicate that the high-strain change-over probably occurred as an open, volume-gain system involving silicification. In the case of the Møre–Trøndelag Fault Complex, a sinistral strike-slip regime during Devonian time was coeval with regionally extensive top-to-the-SW shear in the country rocks outside the fault zone. Later components of movement along the multiphase fault zone, from latest Palaeozoic to Cenozoic time, were mainly of brittle, dip-slip to dextral strike- or oblique-slip character. © 1998 Elsevier Science Ltd.

INTRODUCTION

The Caledonide orogen of Norway exposes innumerable examples of high-strain zones in a variety of crustal-shortening tectonic settings. These range from wide yet discrete, intra-nappe to nappe sole, east-facing shear zones developed during progressive simple shear modified by flattening strains (Zwart, 1974; Roberts and Sturt, 1980), to the more distributed, commonly anastomosing, local high-strain zones that coalesce with increasing strain into bands of protomylonite and mylonite. Many such zones show evidence of polyphase deformation, and some of the regional, now flat-lying shear and thrust zones may have started off as near-vertical, strike-slip, terrane boundaries (Roberts, 1988) prior to their rotation into near-recumbent attitudes as a result of Scandian (Silurian), Baltica–Laurentia collision and subduction. An additional, complicating factor is that of late-Caledonian crustal extension, precipitated by gravitational collapse of the nappe stack (Roberts, 1967, 1983; Hossack, 1984). This led to reverse-sense reactivation along nappe-sole thrusts and the development of thick zones of top-to-the-west, shear-banded mylonites beneath developing Devonian basins (Norton, 1987; Séranne, 1992).

In this paper, brief descriptions are presented of just three examples of high-strain zones from the Caledonides of Central Norway, which illustrate the diversity of character and scale displayed by these structural features. In particular, emphasis is placed on the differences in character relating to different structural levels, from the more distributed, anastomosing shear zones at the deepest levels, via more discrete, intermediate-level shear zones to the narrow, vertical structures that show ductile-to-brittle changes through time. In one case, a structural study was accompanied by a chemical analytical investigation of the progressive mylonitisation of a porphyritic granite pluton towards the base of a major nappe complex.

REGIONAL SETTING

In Central Norway, the Caledonide orogen is composed of a series of east- to southeasterly transported nappes (Gee, 1975; Roberts and Wolff, 1981; Gee *et al.*, 1985) that were subsequently affected by regional-scale folds and extensional faults, and also transected by one conspicuous, multiphase, strike-slip fault zone (Grønlie and Roberts, 1989). The various nappes have been grouped into four major allochthonous complexes, the Lower, Middle, Upper and Uppermost Allochthons (Roberts and Gee, 1985). This is a tectonostratigraphy that, to a large extent, reflects the original palaeogeography moving outboard from the Baltoscandian platform and miogeocline into more exotic oceanic terranes and ultimately, in the highest allochthon, into rock complexes of probable Laurentian affinity.

Precambrian crystalline rocks dominate the Lower Allochthon in this part of Norway (Fig. 1). In eastern areas and also in Sweden, there are comparatively pristine Proterozoic granitoid and volcanic rocks with a thin Vendian–Cambrian sedimentary cover, and only negligible signs of a Caledonian imprint. Towards the west, these rocks gradually become penetratively foliated, mylonitised and recrystallised as a result of the Scandian deformation, and metamorphic grade reached amphibolite facies and even locally granulite facies on the Fosen Peninsula (Möller, 1988). Moving up in the tectonostratigraphy, the Middle Allochthon is characterised by Neoproterozoic, miogeoclinal, low-grade metasandstones, locally with mafic dykes, and with extensive sheets of strongly Caledonised Precambrian crystallines (Gee *et al.*, 1985). This is overlain by

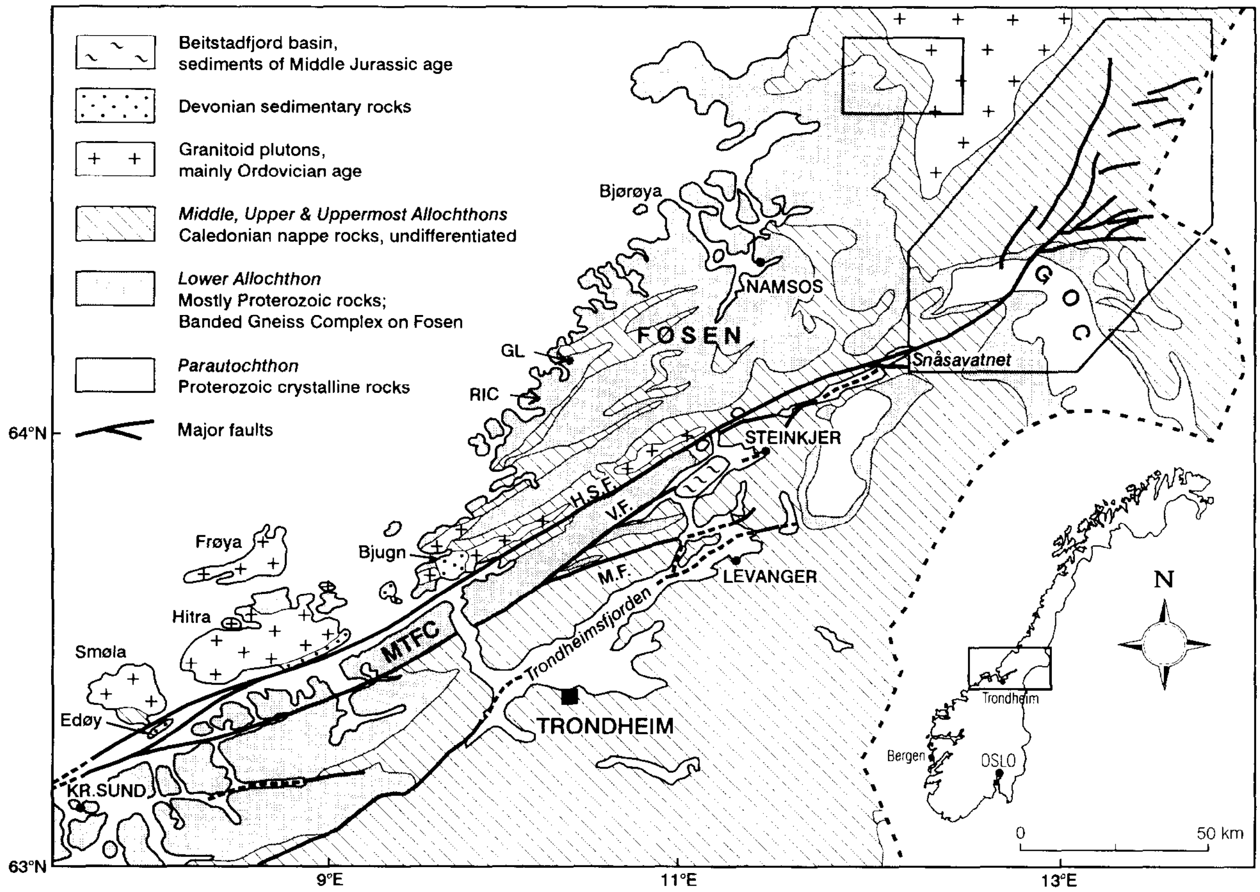

Fig. 1. Simplified outline geological/tectonostratigraphic map of the Central Norwegian Caledonides, adapted from Grønlie and Roberts (1989) and Solli (1989), with modifications after Nordgulen *et al.* (1995). MTFC, Møre Trøndelag Fault Complex; H.S.F., Hitra–Snåsa Fault; V.F., Verran Fault; M.F., Mosvik fault; GL, Granholvatnet Lens; RIC, Roan Igneous Complex. The small box in the north is the area of Fig. 3, whereas the larger boxed area in the northeast corresponds to Fig. 6.

sedimentary and magmatic rocks of the Seve Nappes of the Upper Allochthon, part of the continent-to-ocean transition zone; and this, in turn, is superposed by ophiolitic, island arc and back-arc marginal basin units of the Köli Nappes, derived largely from within and peripheral to the Iapetus Ocean (Roberts and Gale, 1978; Grenne *et al.*, 1980; Furnes *et al.*, 1985). All these units show evidence of more ductile, higher strains and higher metamorphic grade towards the west. By comparison, the Uppermost Allochthon is characterised by abundant granitic rocks of Ordovician to Silurian age (Nordgulen *et al.*, 1993) cutting diverse Proterozoic gneisses, a granitoid magmatic association that is foreign to Baltica. Detailed descriptions of all these nappe complexes and their internal deformation, illustrated by NW–SE cross-sections, can be found in Gee *et al.* (1985).

As noted above, a widespread late-Scandian vertical shortening subsequently affected the nappe pile, and led to the development of a ubiquitous flat-lying crenulation cleavage in appropriate lithologies (Roberts, 1967, 1979). Along many nappe boundaries, top-to-the-west shear bands and related small folds overprinted the contractional structures of the mylonite zones (Möller, 1988; Sjöström *et al.*, 1991), whereas discrete extensional detachments were generated elsewhere. Some of these flat-lying extensional faults have a wide regional extent in southern Norway (e.g. Hossack, 1984; Norton, 1987). In addition, several major, near-vertical faults dissect the tectonostratigraphy, one of which, the Møre–Trøndelag Fault Complex (MTFC), can be followed throughout Central Norway (Grønlie and Roberts, 1989) and offshore, into the northern North Sea (Doré *et al.*, 1997). Aspects of the multiphase deformation that affected the MTFC will be discussed briefly later in this account.

HIGH-STRAIN ZONES

The examples described here are chosen with the purpose of illustrating the diversity of structural and tectonostratigraphic scenarios that preserve well-exposed zones of confined, high strain in this part of the Caledonide orogen. The geological settings of each example are quite different, and consequently, the deformation products, meso- and microstructures, show an interesting variety of form and properties.

Fosen Peninsula; Banded Gneiss Complex

The Fosen Peninsula of western Trøndelag (Fig. 1) forms a part of the Western Gneiss Region, exposing some of the deepest levels of the Caledonian orogen. It comprises Palaeoproterozoic crystalline complexes of the Lower Allochthon or Parautochthon and supracrustal rocks of higher, far-travelled, Caledonian thrust sheets (Johansson, 1986a; Roberts, 1986; Möller, 1988). The Precambrian crystalline rocks, which have yielded protolith ages (U–Pb, zircon) between *c.* 1830 and 1640 My (Johansson, 1986a; Schouenborg *et al.*, 1990), originally comprised part of the cratonic margin of Baltica and were affected by a variable ductile deformation and metamorphism during the Scandian collisional orogeny (Tucker *et al.*, 1987; Schouenborg *et al.*, 1990; Dallmeyer *et al.*, 1992). The intensity of Scandian deformation increases from east to west, affecting also the suprajacent nappe units to the extent that correlations with established allochthons occurring further to the east are insecure (Roberts, 1986).

The extent of Caledonisation in the Fosen district is such that the protolith granitic to tonalitic, migmatitic orthogneisses and basic rocks with some supracrustal units have generally been reworked into strongly banded, gneissic *L–S* tectonites (Johansson, 1986a; Roberts, 1986; Möller, 1988). Möller (1988) adopted the informal term 'Banded Gneiss Complex' (BGC) for these rocks, whereas Gilotti and Hull (1993) called them the 'Vestranden Gneiss Complex'. Here and there, lensoid bodies and structures are common, and on scales ranging from a few metres in size to bodies of 5–6 km length, which are clearly visible on satellite images. A closer study commonly shows transitions over a few metres from homogeneous, coarsely foliate and migmatised orthogneiss with mafic sheets inside the lenses into the heterogeneous banded gneisses that typify the BGC (Roberts, 1986) (Fig. 2). In many cases, the zone of transposition of the internal, older fabrics enveloping the lens is a truly high-strain zone, in amphibolite facies, composed of little more than thinly banded, mafic and felsic 'streaks' derived from the protolith lithologies of the lens.

In this same district, along the thrust contact between the BGC and the subjacent Roan Igneous Complex (Fig. 1), high-PT Scandian mylonites carry a NW–SE lineation with both top-to-the-SE ductile-contractional and later top-to-the-NW extensional structures (Möller, 1988). Gilotti and Hull (1993), however, suggested that Caledonian thrust movement here was directed entirely towards the WNW, a notion that gains little support from regional geological considerations. A more likely interpretation is that there was significant, late, extensional reactivation focused along this particular contact, carrying the hangingwall BGC rocks northwestwards across the RIC. Within this same mylonite zone, there are relics of high-P granulite-facies tectonites, indicating that thrusting was initiated at subduction zone depths greater than 50 km (Möller, 1988). Geothermobarometric studies in rocks of both the footwall Roan Igneous Complex and the structurally overlying Banded Gneiss Complex have given PT estimates of *c.* 870°C and 13–14.5 kbar (Johansson and Möller, 1986; Möller, 1990). Sm–Nd dating of a mafic, high-P granulite in the Roan Igneous

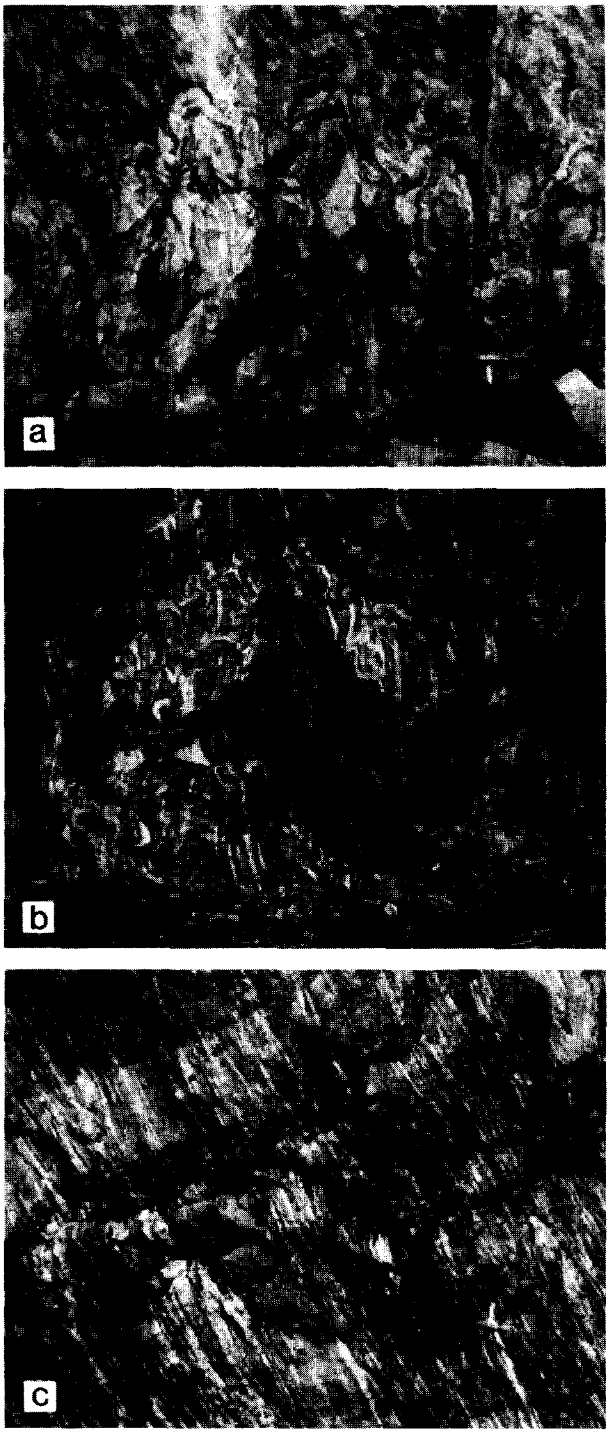

Fig. 2. Transformation of (a) a migmatised granodioritic gneiss with buckle-folded pegmatitic neosome, through (b) a more tectonised variant to (c) a fairly typical banded gneiss; Fosen Peninsula, Osen district, 10–15 km NE of Roan (RIC) (Fig. 1).

Complex has yielded an isochron age of 432 ± 6 My, interpreted to date peak metamorphic conditions (Dallmeyer *et al.*, 1992).

A lensoid body of the type noted above, the 'Granholvatnet lens', has been described by Johansson (1986a,b). This body is 2.8 km in length and 0.5 km thick, consists of orthogneiss, chaotic migmatitic veining and coronitic textured basic rocks, and is enveloped by an intensely sheared zone of transposition. Elsewhere on Fosen, comparable lenses measuring up to 6 km x 2 km, with similar skins of highly strained, transposed rocks and fabrics, have been detected in a photogeological study of a 4500 km^2 area (Roberts, 1986).

In one coastal area of orthogneisses, a lens of massive gabbro on Bjørøya has been converted into garnet amphibolite by intense shear along its margins, and the adjacent gneisses were remobilised by shear heating, with the newly formed granitic vein-neosome back-veining the garnetiferous high-strain zone (Roberts, 1986). As well as these mappable megalenses, small, comparatively isotropic lensoid bodies retaining pre-Caledonian fabrics can be identified in outcrop in many places—solitary relics that have survived the intense, Scandian, ductile strains that pervaded the tectonically shortened margin of Baltica at this tectonostratigraphic level.

Mylonitisation of a porphyritic granite: textures and geochemistry

A high-strain zone of rather more homogeneous character and somewhat lower metamorphic grade occurs at an intermediate structural level at the base of the Helgeland Nappe Complex in the Uppermost Allochthon (Fig. 3). In the area east of Kongsmoen, a coarsely porphyritic granite of the Late Ordovician/Early Silurian Bindal Batholith (Nordgulen *et al.*, 1993) displays a progressive textural, microstructural and mineralogical transformation via lensoid, augen granite-gneiss into an increasingly higher strain facies of blastomylonites, mylonites and sporadic ultramylonites (Roberts *et al.*, 1983) (Fig. 4a, b). Foliation in the augen granite-gneiss and mylonites dips at moderate angles to the ESE, and the zone of high-strain mylonites is at least 200 m thick. Kinematic indicators, mostly shear bands, indicate a syn-mylonitisation, top-to-the-ENE sense of contractional shear (Roberts and Nissen, 1996); but a subsequent cataclastic, extensional component has also been registered, with a top-to-the-east shear sense (Fig. 4c).

A variety of features accompany the conversion from granite to mylonite. These include (1) a gradual grain-size reduction of all constituent minerals, allied to (2) the progressive development of a mylonitic foliation, with phenocrysts of microcline up to 3 cm across gradually reduced to relict clasts of < 1 mm in size; (3) polygonisation of quartz, with at least two separate neocrystallisations, a dynamic process of geometric softening; (4) the gradual, but increasing, presence of string- and flame-perthite; (5) sericitisation of plagioclase; and (6) chloritisation of biotite. With increasing strain, quartz content increases markedly in the mode at the expense of feldspars, especially plagioclase, and mafic minerals decrease in volume (Roberts *et al.*, 1983).

A controversial topic in relation to mylonite genesis is the relative significance of mechanical and chemical processes, and, in the latter case, whether we are dealing with an isochemical or an open system. In general, however, low-grade shear zones facilitate the channelling and connectivity of fluids (Watson and Brennan, 1987), which in turn have a bearing on deformation mechanisms and rock rheology. The clear and progressive transformation of the Bindal granite via augen granite to mylonite presented a good opportunity to study possible chemical changes associated with this deformation.

An analytical study (based on 21 analyses of granite and seven of mylonites) has, in fact, shown that the transformation was not isochemical (Roberts and Nissen, 1996). With increasing ductile deformation, SiO_2 shows a fairly marked wt% increase from 68% in the protolith granite to 74% in the mylonites. Other major oxides and principal trace elements show negative changes, though to varying degrees: Al_2O_3, for example, appears to drop 15%, whereas K_2O decreases only 3%. The full chemical analytical data are contained in the report by Roberts and Nissen (1996).

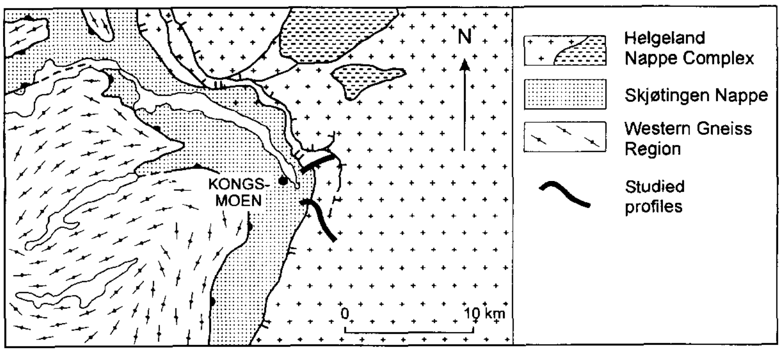

Fig. 3. Simplified map of the Kongsmoen district showing the locations of profiles used in the study of the transformation of porphyritic granite to mylonite, at the base of the Helgeland Nappe Complex. The division of the rocks of the Helgeland Nappe Complex is into granites/granodiorites (crosses) and schists/gneisses (dashed ornament).

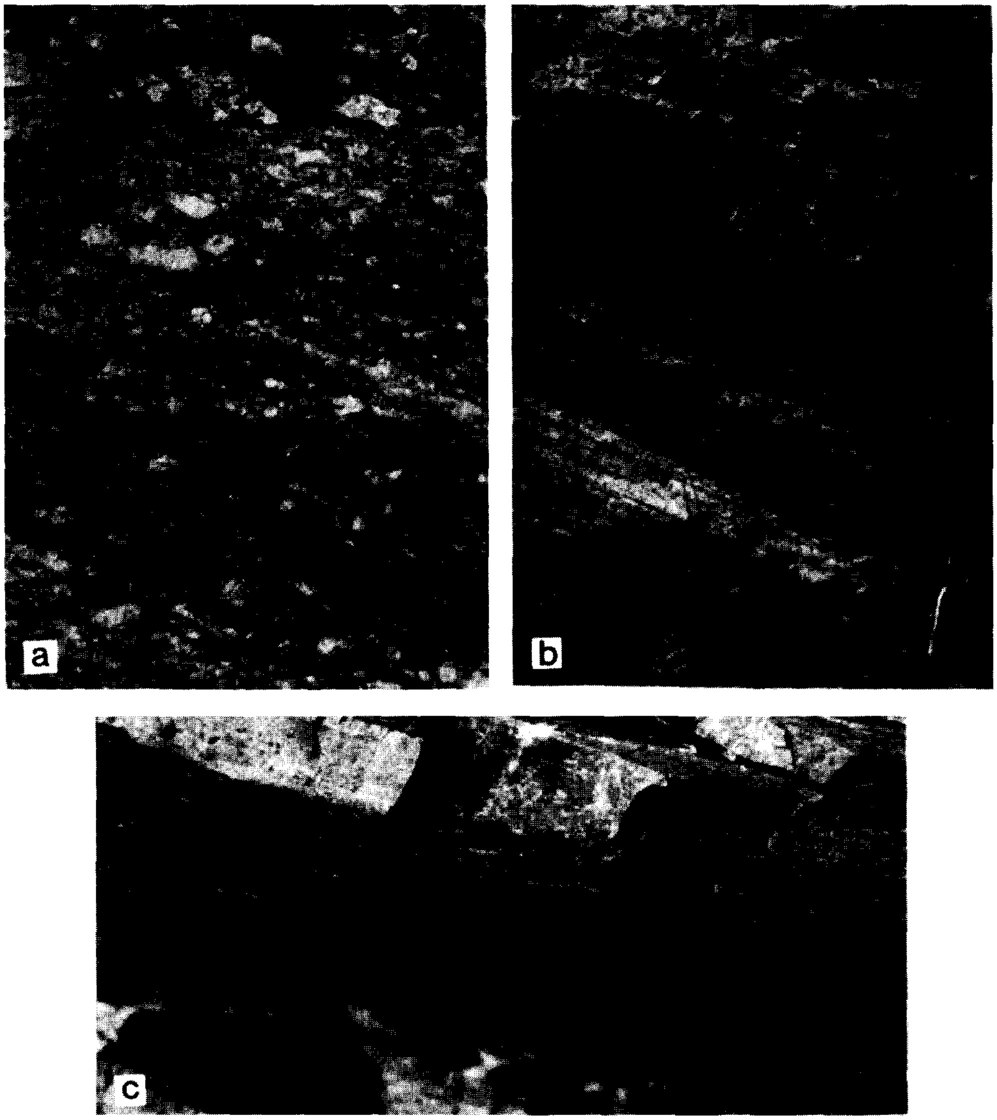

Fig. 4. (a) Augen granite-gneiss, derived from the Bindal porphyritic granite; (b) thin-banded platy mylonite with bands of ultramylonite, derived from the augen granite; (c) ultramylonite (pale grey layer above the pencil) with a stepped surface along the interface between the ultramylonite and underlying augen granite. The steps, with a faint lineation on the surface, indicate a comparatively late, E-directed extensional movement. All photographs taken looking approximately towards the north; Aunvatnet, northeast of Kongsmoen (see Fig. 3).

While these various apparent changes can be explained in terms of modal change, and especially in the breakdown of the feldspars, the actual fate of all these disappearing elements is less easy to comprehend. They may, however, be expected to reside in vein-mineral phases or intra-foliation segregations within or marginal to the chemically mobile high-strain zone, rather than having been extracted and deposited outside the system. A more plausible explanation, considered briefly below, is that we are dealing with *apparent* losses, caused by the diluting effect of a marked increase in silica to the system via aqueous fluids during the mylonitisation process. This leads on to the importance of assessing volume changes (Gresens, 1967) when comparing the end-member, bulk rock compositions in deformation-alteration processes of this kind.

An important criterion in shear-zone classification is that of the change in rock volume seen in relation to element gain or loss (Gresens, 1967; Ramsay, 1980; Bailey *et al.*, 1994). In this way, such high-strain zones have been categorised as either volume-loss or isovolume shear zones (with volume-gain usually placed in the isovolume category) (Tobisch *et al.*, 1991). Based on a study of many shear zones around the world, Condie and Sinha (1996) devised plots involving normalising protolith/mylonite ratios for selected oxides, in order to discriminate between volume-loss and volume-gain shear. This method of determining the possible volume change involved in this particular mylonitic shear zone has been applied to the seven samples of Bindal mylonite (Fig. 5), and it is fairly clear that in this case we are dealing with the isovolume/volume-gain category of shear zone. When, in addition, one considers the *c.* 9% increase in SiO_2 coupled with the marked

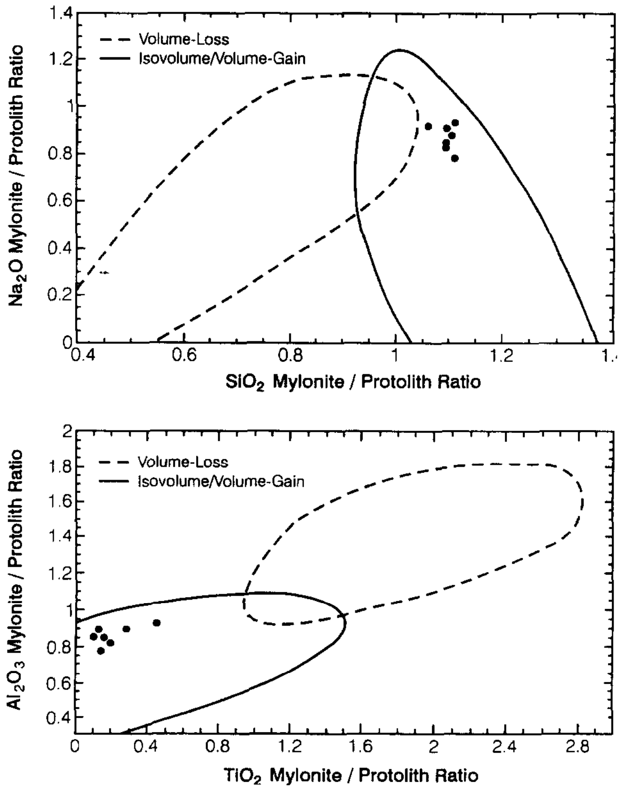

Fig. 5. Plot of concentration ratio, mylonite/granite protolith, for (a) Na_2O and SiO_2 and (b) Al_2O_3 and TiO_2 for the seven mylonites/ultramylonites used in this study. The fields for volume-loss and isovolume/volume-gain shear zones are those for shear zones world-wide calculated from isocon analyses, and are based on data presented by Condie and Sinha (1996).

increase in the modal quartz content, which suggests that a process of fluid-enhanced silicification appears to have accompanied the mylonitisation, then it is probable that a small volume increase may have occurred during this particular high-strain reworking of granite to mylonite.

The Møre–Trøndelag Fault Complex

The ENE–WSW-trending Møre–Trøndelag Fault Complex (MTFC) (Fig. 1) constitutes one of the most prominent, multiply reactivated fault zones within the Norwegian Caledonides. Although hitherto better known as the Møre–Trøndelag Fault Zone, this term has now been superceded by the more formal designation Møre–Trøndelag Fault Complex (Blystad *et al.*, 1995). Diverse field and laboratory studies over the last 10 years have provided a wealth of evidence indicating that this 10–20 km-wide fault zone has a prolonged history of polyphase displacement varying from strike-slip through oblique-slip to dip-slip in varying temperature and strain regimes (Grønlie and Roberts, 1987; Grønlie and Roberts, 1989; Bøe and Bjerkli, 1989; Grønlie and Torsvik, 1989; Grønlie *et al.*, 1991, 1994; Séranne, 1992). Temporal constraints, derived mostly from isotopic (Sm–Nd, K–Ar) and fission track dating and palaeomagnetic studies, have indicated a number of principal stages of movement. These include ductile sinistral offset in latest Silurian to Early Devonian time; and ductile-to-brittle (or more brittle at younger stages) dip-slip and mainly dextral strike-slip displacements in Late Devonian, Permo-Triassic, Late Jurassic–Early Cretaceous and Late Cretaceous–Early Tertiary time. Some neotectonic movement has also been inferred. Studies of the fault complex along its offshore, southwestward extension into the northern North Sea have helped to confirm much of this reactivation history (Bucovics *et al.*, 1984; Fossen, 1989; Doré *et al.*, 1997).

Towards the northeast in the county of Nord-Trøndelag, the bulk lateral offset along the MTFC on the southern flank of the Grong–Olden Culmination (GOC) is no more than 4–5 km, and this diminishes northeastwards. Air-photo interpretations of fault patterns in and adjacent to the GOC, with fieldwork control, have been presented by Stel (1988) and Heim (1992), and a study based on satellite imagery has just been completed (E. Bråstein, 1997). Northeast of the GOC, strain along the fault zone appears to have diminished and to have been dispersed in a horsetail splay, with many minor E–W faults involved (Fig. 6). From the 1:50 000 map picture, it is difficult to say whether this represents a compressional or extensional splay termination. However, since fault rocks, northeast of the GOC, if developed at all, are mainly cataclasites with some breccias and gouge, this favours either a Late Palaeozoic or a Mesozoic movement history, which, in turn, suggests the development of an extensional terminal splay. A transfer zone may also be involved whereby the strain may have been transmitted across to a subparallel fault transecting the Gjersvik Nappe, and with some strain accommodation by extension or oblique-slip along pre-existing major and minor thrust contacts.

The highest strains involved in the shear history of the MTFC, as indicated by meso- and microstructures and appropriate lithologies, are those associated with the latest Silurian to Devonian, sinistral displacements (Grønlie and Roberts, 1989; Séranne, 1992). These components of movement are discussed briefly here. A fundamental feature of the two, steeply NW-dipping, major faults that delineate the MTFC on the Fosen Peninsula, the Hitra–Snåsa and Verran Faults (Fig. 1), is that they postdate the stacking of the Scandian nappes. Nevertheless, there is evidence to suggest that a precursor fault in the basement (Grønlie and Roberts, 1989) also caused deflections (to NE) in the normal E- to SE-directed thrust transport in this region (e.g. Séranne, 1992).

There is now general agreement that the principal phase of ductile deformation along the MTFC coincided with sinistral strike-slip movement in Early Devonian and even latest Silurian time. Studies along the Snåsa–Hitra, Verran and parallel faults have recorded major developments of mylonites, with kinematic indicators clearly signifying left-lateral shear (Grønlie *et al.*, 1991; Séranne, 1992). This high-strain regime also affected the

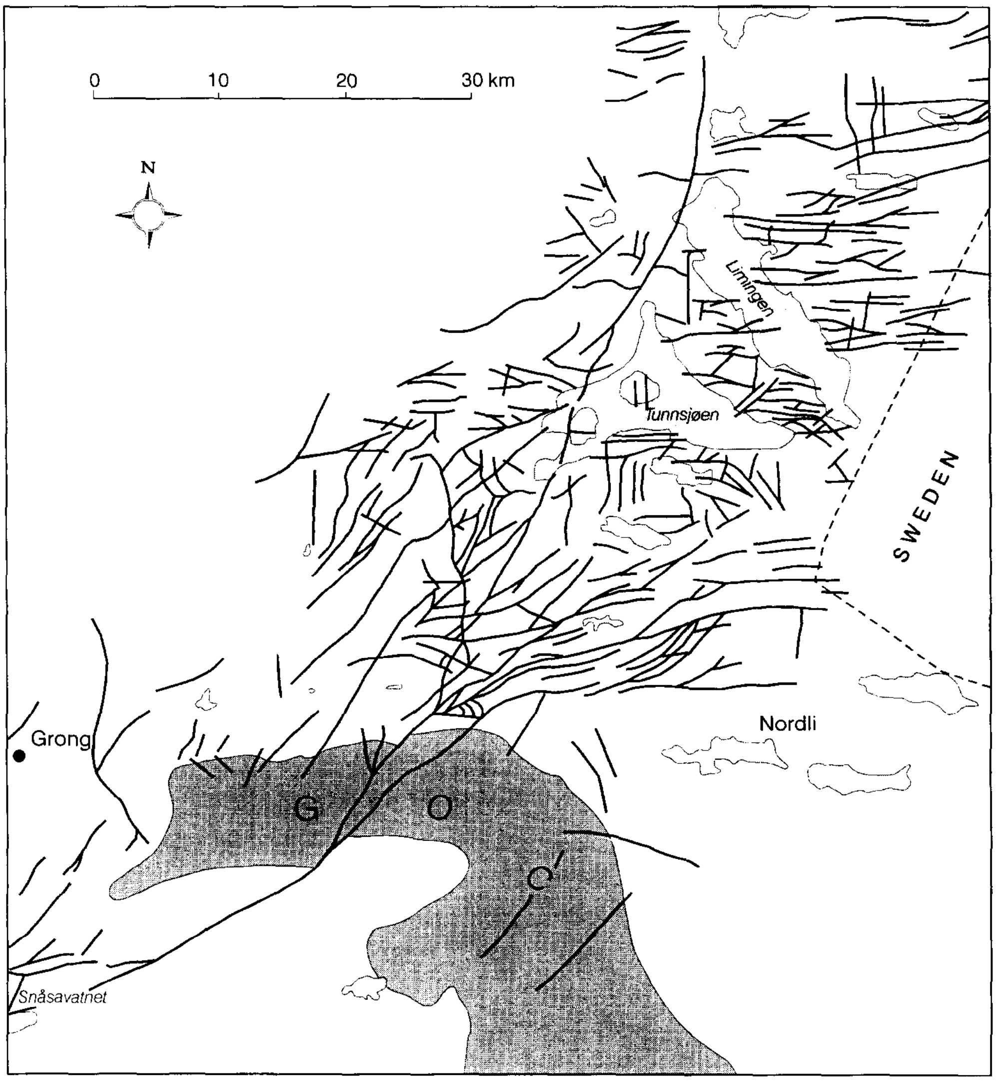

Fig. 6. Fault patterns along the northeastward extension of the Møre–Trøndelag Fault Complex, north of the Grong–Olden Culmination (GOC); for the location (e.g. Snåsavatnet and the Norwegian–Swedish border), see the northeastern corner of Fig. 1. The faults shown have been compiled mainly from the existing 1:50 000 preliminary bedrock geological maps published by the Geological Survey of Norway.

country rocks, whereby protomylonitic foliation trajectories are seen to be drawn into the loci of higher strain along the faults. At the same time, oblate fabrics in country-rock gneisses pass into prolate close to the faults, and a marked, fault-parallel stretching lineation is developed.

In the southern and western parts of the Fosen district, a regional NE–SW lineation is common with clear indications of top-to-the-SW shear and strain-induced pegmatite development, an event dated by the Rb–Sr method, on muscovite porphyroblasts, to *c.* 389 My, i.e. Mid-Devonian time (Piasecki and Cliff, 1988). A detachment surface beneath a Devonian basin succession in one area, near Bjugn, with top-SW shear, is considered to be of the same age (Séranne, 1992). Immediately southwest of Fosen, this same top-SW shear, which is sinistral on steeply NW-dipping high-strain zones, is clearly discernible in the country rocks (Séranne, 1992), and has also been recorded some 100 km further to the southwest in the Western Gneiss Region (Robinson, 1995).

Many of the mylonites occurring along the principal faults of the MTFC show features indicative of a strong retrogression (Grønlie *et al.*, 1991) that preceded a second stage of sinistral shear leading to cataclasis and brecciation in the ductile-to-brittle transition field along these same faults in about Late Devonian/Early Carboniferous time. This is assumed to be the same late episode of sinistral shear recorded by Séranne (1992) along faults that cut lithified Middle Devonian sediments. During later stages of its reactivation history, the MTFC has incurred high strains of rather more discrete character, evidenced by ultracataclasites and local pseudotachylites within complex breccias, some hydrothermally altered and others radioactive and thorium-enriched. Details of this later, more brittle evolution are contained in Grønlie and Torsvik (1989) and Grønlie *et al.* (1991, 1994).

CONCLUSIONS

The Caledonides of Central Norway expose high-strain shear zones of widely variable character, metamorphic grade and scale. The examples described here were generated at different structural levels at conditions ranging from high-PT granulite facies to amphibolite facies in the case of Scandian, thrust-related mylonites; and in the ductile and ductile-to-brittle transition regimes for mylonites and ultracataclasites along the multiply reactivated Møre–Trøndelag Fault Complex. In an example taken from a transformation of granite to mylonite, geochemical data show that the progressive change occurred as an open, small volume-gain system involving a measure of silicification.

In the case of the MTFC, a sinistral strike-slip and otherwise regionally extensive, top-to-the-SW, shear regime characterised the Devonian period. These displacements were succeeded by several fault rejuvenations of mainly dip-slip to dextral strike-slip character, generating many different types of breccia, in latest Palaeozoic to Cenozoic time.

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