Rb-Sr dating of strain-induced mineral growth in two ductile shear zones in the Western Gneiss Region of Nord-Trøndelag, Central Norway

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In the Bjugn district of the northern part of the Western Gneiss Region, Nord-Trøndelag, a basement gneiss — cover nappe boundary is marked by a thick zone of ductile shearing, in which a layer-parallel mylonitic fabric with related new mineral growth overprints and retrogresses a previous fabric associated with a granulite(?) facies mineral assemblage. Related minor shear belts contain abundant new minerals and vein systems, including pegmatites, believed to represent strain-induced products formed at the time of the shearing movements.
Central parts of two large muscovite 'books' from such a pegmatite yielded Rb-Sr, Early to Middle Devonian ages of 389 ± 6 and 386 ± 6 Ma, interpreted as indicating the approximate time of pegmatite formation and of the shearing. Small, matrix-size muscovite and biotite grains from the host mylonite gave ages of, respectively, 378 ± 6 and 365 ± 5 Ma, thought to relate to post-shearing uplift and cooling.
East of the Verran Fault, a major shear zone also contained syn-shearing pegmatites from which a large muscovite book yielded a Rb-Sr age of 4214 ± 6 Ma, interpreted as indicating the time of the pegmatite formation during Scandian nappe movements. This shear zone has been subsequently reactivated by later shearing associated with regional retrogression.
The fabrics of the major and minor shear zones in Bjugn, and of the late shearing east of the Verran Fault, are characterised by a NE-SW trending stretching lineation. Kinematic markers indicate a sense of layer-parallel, subhorizontal overthrusting movements *not* towards the southeast, but towards the southwest, parallel to the strike trend of the orogen. This suggests that this particular region may have had a different tectonic history to that of adjacent parts of the central Scandinavian Caledonides.

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Introduction

The geology of the Western Gneiss Region of Nord-Trøndelag (Fig. 1), also known as 'Vestranden', was until recently amongst the least well known in the Scandinavian Caledonides (for reviews see Gorbatschev 1985, Roberts 1986). Its most common rocks are granitic (sensu lato) gneisses and metabasites of basement aspect and of probable Proterozoic age. These gneisses are interfolded with distinctive, supracrustal 'cover' assemblages of gneissic calc-psammites and calc-schists with metabasites and local marbles. Although both the gneisses and the supracrustal rocks show polyphase deformation sequences and a pervasive development of amphibolite facies mineral assemblages, they locally preserve relics of earlier granulite-facies mineralogy (Johansson 1986, Möller 1986). The boundary between these rock units is generally followed by a zone of spectacular ductile shearing. The supracrustal assemblages have been variously correlated with the Early Palaeozoic rocks of the Gula and Støren Nappes (Wolff & Roberts 1980, Roberts & Wolff 1981, Johannson 1986), and with Proterozoic units of the composite Seve Nappe (Gee 1978, Gee et al. 1985). Roberts (1986) further suggested that still older supracrustal assemblages may perhaps also be involved.

A preliminary investigation was carried out on some of the shear zones in the Western Gneiss Region in Bjugn, and in Leksvik (Figs. 1, 5, 7). The ages of minerals believed to have been generated during the shearing movements have been obtained isotopically from two shear zones. This paper describes

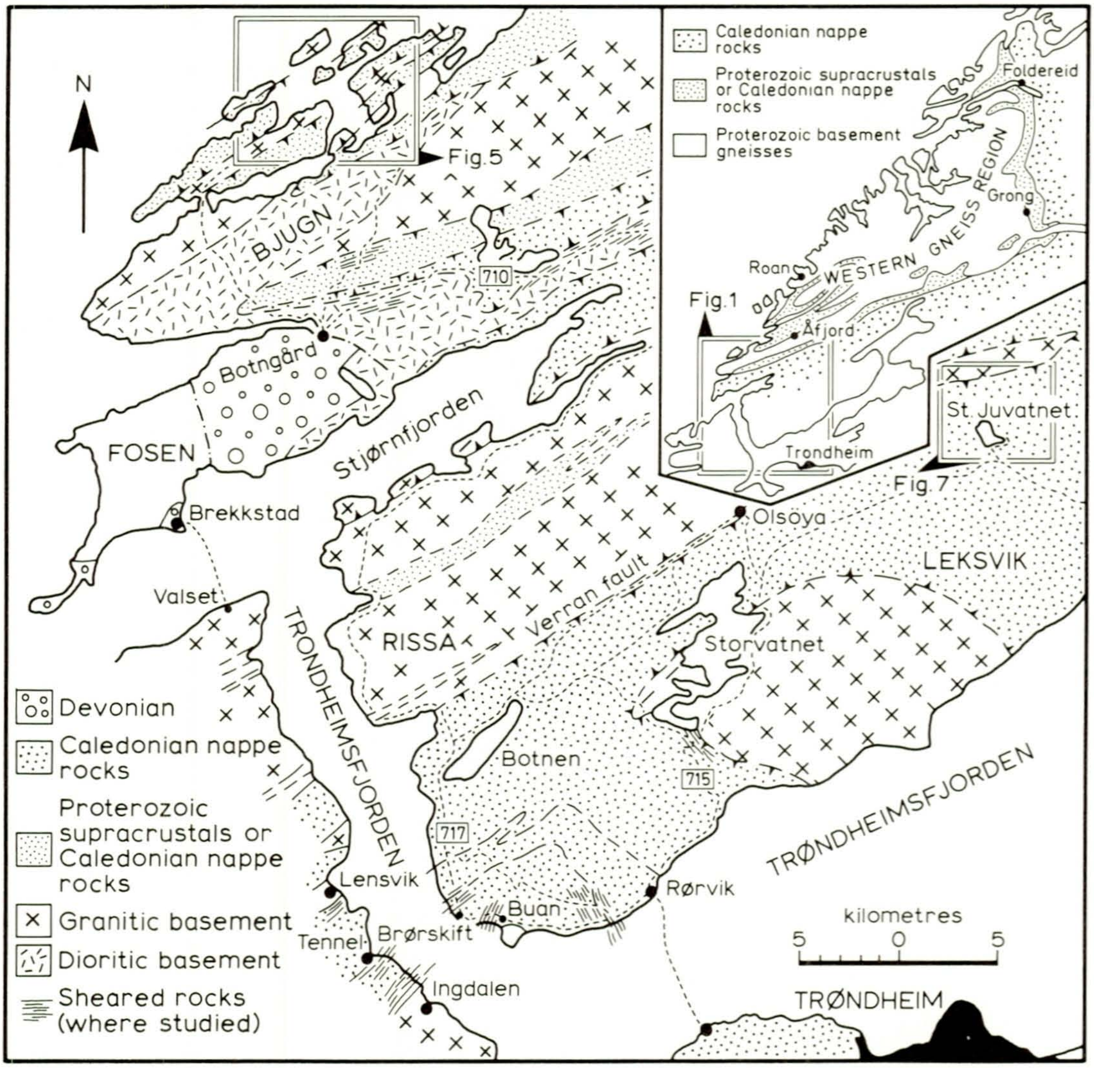
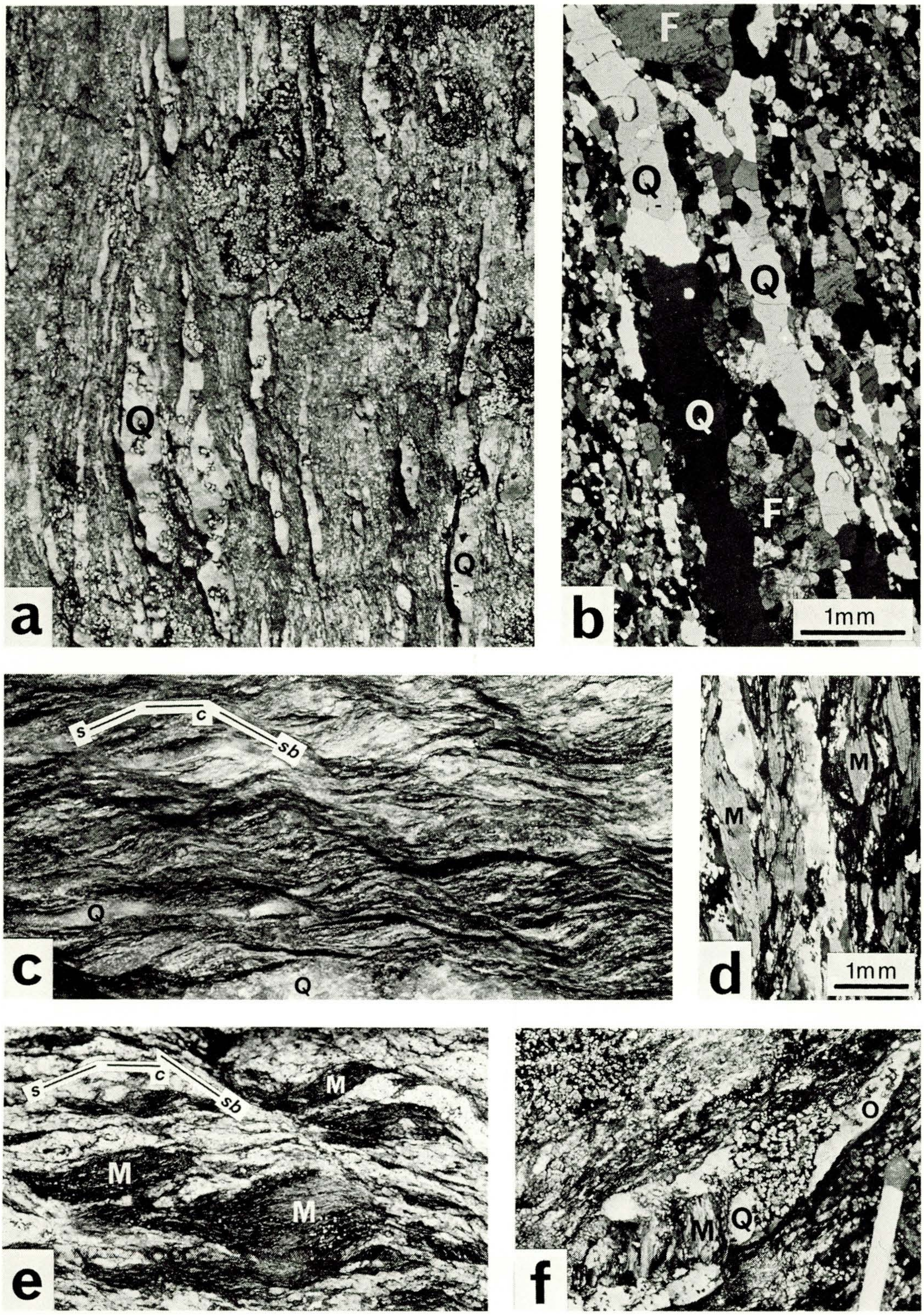


Fig. 1. Outline geological map of the area northwest of Trondheim, showing locations of areas described in the text. Geology modified after the NGU 1:250,000 map-sheet 'Trondheim' (Wolff 1976), Gee & Wolff (1981), Gee et al. 1985 and Tucker (1986). Inset: location of the area in relation to the Vestranden (Western Gneiss region) district of Nord-Trøndelag.

Fig. 2.
(a) Typical swarm of small quartz plates (Q), in a ductile mylonite derived from a semipelitic garnet-biotite schist of formation 9 in Fig. 7, 1km west of Slettliheia. Natural size.
(b) Highly elongate quartz grains (Q) forming quartz plates in a mylonite. In between the plates, plagioclase (F at top-centre), and a granular aggregate after plagioclase (F at bottom-centre). Near Rømmen in Fig. 5.
(c) Well developed S-C (s & c) and shear band (sb) foliations in a phyllonite (mica-rich mylonite) with quartz plates (Q); sense of shear transport is right-lateral. In an adjacent domain, S-C foliations occur without shear bands. Natural size, southernmost road-cut in the road to Ulladalen, Åre, Sweden.
(d) Matrix muscovitisation: muscovite (M, grey colour) replaces biotite in the matrix of the mylonite featured in Fig. 4b. The parent rock of the mylonite (Fig. 4a) does not contain muscovite.
(e) Muscovite porphyroblasts (M) in a mylonite derived from a semipelitic schist, deformed during a later phase of the same shearing event, or during a subsequent shearing event, with the development of S-C foliations (s & c) and shear bands (sb). Some back-rotation on shear bands steepens the attitudes of the S-foliation. Sense of shear transport is right-lateral. Natural size, Fleur de Lys Supergroup, Newfoundland, Canada.
(f) Muscovite porphyroblast (M) growing in a quartz plate (Q) in the mylonite of Fig. 4b. Near natural size.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the structural-isotopic method used, reports on the results obtained, and comments on their regional implications.

Method of dating in shear zones

The method is based on the recognition that, at the time of ductile shearing, new, strain-induced rock products (minerals and systems of veins) nucleate in the mylonites of the shear zones (Wintsch 1975, Andréasson 1979, Andréasson & Gorbatschev 1980, Piasecki & van Breemen 1983, Wintsch & Knipe 1983, Piasecki 1984, Lindqvist & Andréasson 1987). Here we describe those products which, once identified in a shear zone, can be dated isotopically, providing a means for dating the time of movement in the shear zone. Others are described because they can be used to derive the sense of tectonic transport in shear zones.

The strain-induced products in shear zones

The rocks which host the syn-shearing products range from protomylonites through blastomylonites and mylonites to ultramylonites (White 1982) which commonly show cyclic changes in strain rate (Wintsch & Knipe 1983). They are characterised by grain-size reduction (cf. Fig. 4a & b), attenuation, the development of stretching (extentional) lineations, and also of S-C foliations and shear bands as illustrated in Fig. 2c & e, and defined, respectively, by Berthé et al. (1979) and by Gapais & White (1982); (see also White et al. 1980, Weijermars & Rondeel 1984, White et al. 1986). Folds formed during the shearing movements are intimately related to the fabrics of the evolving shear zone. They are asymmetric, drag-like structures (Figs. 3c & 4e) which usually fold an earlier-formed mylonitic fabric, whilst that mylonitic fabric which was forming at the time the folds were developing defines their axial surfaces (Figs. 3c & 6). The folds verge in the direction of transport in the shear zone (Figs. 3c & 4e). Their hinges rotate into subparallelism with this direction, commonly becoming curvilinear in the process, and in some cases developing into sheath folds (Fig. 4f; for the concept, see Carreras et al. 1977, Cobbold & Quinquis 1980).

In semipelitic and siliceous lithologies sheared under amphibolite facies conditions in the presence of fluid, the new products are quartz veins, mica, feldspar, garnet and rarer pegmatites, referred to as 'shear-zone pegmatites' (Piasecki & van Bremen 1983, Piasecki 1984).

Quartz plates and quartz ribbons. The most common syn-shearing products form by an apparent segregation of quartz into veins, which can be oblate (plates) or elongate (ribbons). These range in size from microscopic to more than 20 metres in length, and are usually subparallel to the mylonitic foliation (the C-fabric) of their host rocks (Figs. 2a & b, 4b, c & d). In the ribbons, the direction of maximum extension corresponds with the orientation of other extensional fabrics in the host mylonites. Such veins may also be present in rocks outside the shear zones, but they reach swarm proportions in the ductile mylonites of the shear zones (Figs. 2a, 3a, 4b & c). Such swarms of quartz plates characterise Precambrian and Palaeozoic ductile shear zones in Scotland, Grenvillian shear zones in Ontario, Canada (Culshaw & Fyson 1984), and the Gander Terrane in Newfoundland (Piasecki 1988). In calcareous rocks, plates or ribbons of carbonate accompany those of quartz (Beach 1981), or quartz plates carry porphyroblasts of carbonate.

Micas. Many ductile shear zones are characterised by abundant growth of new muscovite, which takes several forms. One is the replacement of small matrix biotite and K-feldspar in the rocks undergoing mylonitisation by new matrix muscovite (as at Jøssund, see p. 44, and Figs. 4a, 4b and 2d). The result is commonly that of extensive matrix muscovitisation in the mylonites (see also Andréasson 1979). Another form of muscovite growth is the nucleation of porphyroblasts, which sometimes measure from 2 cm to over 10 cm across (001). These form either separately (Fig. 2e), or in association with recrystallising quartz (Fig. 2f).

Garnet. Strain-induced growth of garnet commonly results in rotated porphyroblasts with 'snowball' structures, or in tabular-shaped porphyroblasts, distinct from the earlier garnet of the parent rocks and from subsequent garnet (see Fig. 6a, b & c in Piasecki & van Breemen 1983). Such garnetiferous, muscovitised mylonites with swarms of quartz plates often have the field aspect of quartz-garnet-muscovite schists, and have sometimes been mistaken for primary lithologies, metamorphosed and deformed to thinly foliated schists.

Feldspar. New feldspar, which may be an alkali feldspar or plagioclase depending on the rock composition and the chemical conditions in the shear zone, commonly takes the form of porphyroblasts which grow in the shear fabric (Fig. 4d). It generally accompanies the quartz plates and pegmatites (Fig. 3c). The size and the frequency of occurrence of such feldspar porphyroblasts (and also of muscovite porphyroblasts) can usually be seen to be spatially related to the pegmatites, indicating that they are all products of strain-induced segregation and neocrystallisation.

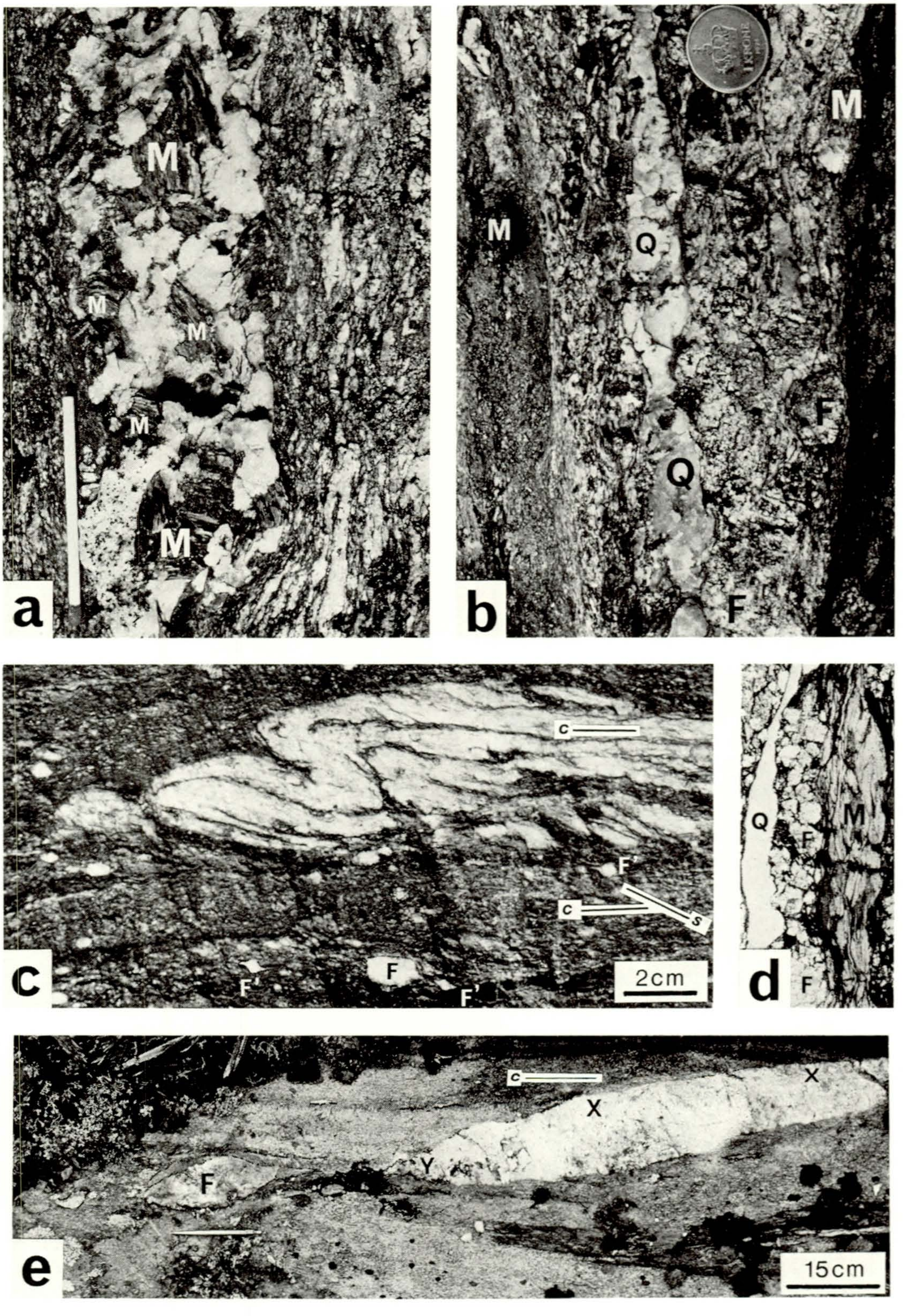
Shear-zone pegmatites. The growth of muscovite porphyroblasts inside quartz plates gives rise to unusual muscovite-quartz pegmatites, which seem to be rocks confined to shear zones (Fig. 2f). The growth of feldspar together with quartz plates ($\pm$ muscovite and garnet) results in 'quartz-plate pegmatites' of more usual mineralogy (Figs. 3a, b, c & e). Their syntectonic nature can be demonstrated by their relationship to the S-C fabric in the host mylonites (Fig. 3e); or they can be observed to have formed by the strain-induced recrystallisation of quartzofeldspathic layers (bedding) in metasediments, or, as a result of the shearing of rocks which previously contained no pegmatites (pp. 44-45; cf. Figs. 4a with 4b & 3a). Such pegmatites generally form small knots, lenticles and subconcordant veinlets, a few millimetres to a metre thick, which typically accompany more voluminous swarms of quartz plates in the mylonitic rocks of the shear zones. More rearly, related pegmatites occur outside the shear zones, where they may occasionally reach several metres in thickness.

Relationship between mineral growth and deformation in the shear zones

The quartz plates appear to have initially formed with very elongate grains (Fig. 2b), their elongation ratios sometimes exceeding 20:1. In S-C mylonites, the quartz plates (and also porphyroblasts of tabular garnet) are commonly subparallel to the plane of the C-fabric (Figs. 2a, 3a, 4b): they seem to have either formed in that plane, or have been rotated into it (cf. Fig. 3e). Porphyroblasts of muscovite and feldspar show variable orienation in relation to the C-fabric. Some of these products may represent static growth (e.g. porphyroblasts at F in Fig. 3c and at A in Fig. 4d). Such 'blastesis' may occur during intervals between increments of simple-shear movements which can be expected to affect small-scale domains of a shear zone (cf. Wintsch & Knipe 1983). On the other hand, some quartz plates and shear-zone pegmatites can be seen to have formed subparallel to the S-fabric plane, indicating that mineral growth seems to have coincided with the simple-shear movements (Fig. 3e).

With continued shearing, the porphyroblastic products deform, some becoming indistinguishable from porphyroclasts (relics of 'strong' minerals derived from the source rocks of the mylonites, as the kyanite in fig. 4c). From then on, both evolve together, providing kinematic indicators of the sense of movement in the shear zone (Simpson & Schmid 1983, Passchier & Simpson 1986). Thus, feldspar porphyroblasts and porphyroclasts deform into distinctive forms with tails of a finer grained feldspar aggregate (F'in Fig. 3c). On further shearing they dynamically recrystallise into aggregates of equigranular, polygonal grains, which eventually become stretched out into long lenses and ribbons in the mylonites (F at bottom-centre of Fig. 2b, & F in 3d; see also Figs. 6d to 6g in Piasecki & van Breemen 1983). In quartz plates, the elongate quartz grains strain, recover dynamically and recrystallise into aggregates of grains. Lenses or ribbons of such aggregates of feldspar, and at time also recrystallised quartz plates, seem to resist subsequent metamorphism and deformation: and in some Scottish Proterozoic mylonites reworked during Palaeozoic orogenic events, they provide the only relics of previous mylonite fabrics. Muscovite porphyroblasts strain into augen which commonly become separated into 'tectonic fish' (Lister & Snoke 1984; see also Fig. 3e). On further deformation they recrystallise into aggregates of smaller grains (Fig. 3d), which may later become smeared out into thin muscovitic stringers. The shear-zone pegmatites likewise become progressively deformed (cf. Figs. 3a, b, e & c), showing all stages of straining and dynamic recrystallisation.

A striking feature of the strain-induced products in mylonites is how very variably they may be deformed, even on the scale of a single exposure. Thus, intensely deformed peg-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matites, or large feldspars deformed into aggregates of polygonal grains, can coexist in close proximity with little deformed pegmatites or feldspar porphyroblasts which may even overprint part of the mylonitic fabric (F in Fig. 3c, and Fig. 4d). In Scottish shear zones, the equivalence of such apparently contrasting rock-types is supported by similar Rb-Sr ages obtained from muscovite porphyroblasts in such deformed and undeformed pegmatites. Such relationships indicate that:

(a) During the evolution of the shear zone, local increments of shearing movement may have followed separate, subparallel paths, which anastomosed on all scales, and those products which had nucleated in the path of subsequent movements became more deformed than others.

(b) The strain-induced products may have formed episodically during an extended period of shearing (cf. Wintsch & Knipe 1983). This is indicated by the occurrence of early-, late- and post-shearing garnet porphyroblasts and pegmatites (respectively, the most and least deformed) in Scottish shear zones, in which mineral growth locally outlasted the shearing movements (Piasecki & van Breemen 1983, and unpublished work; see also Andréasson & Gorbatschev 1980).

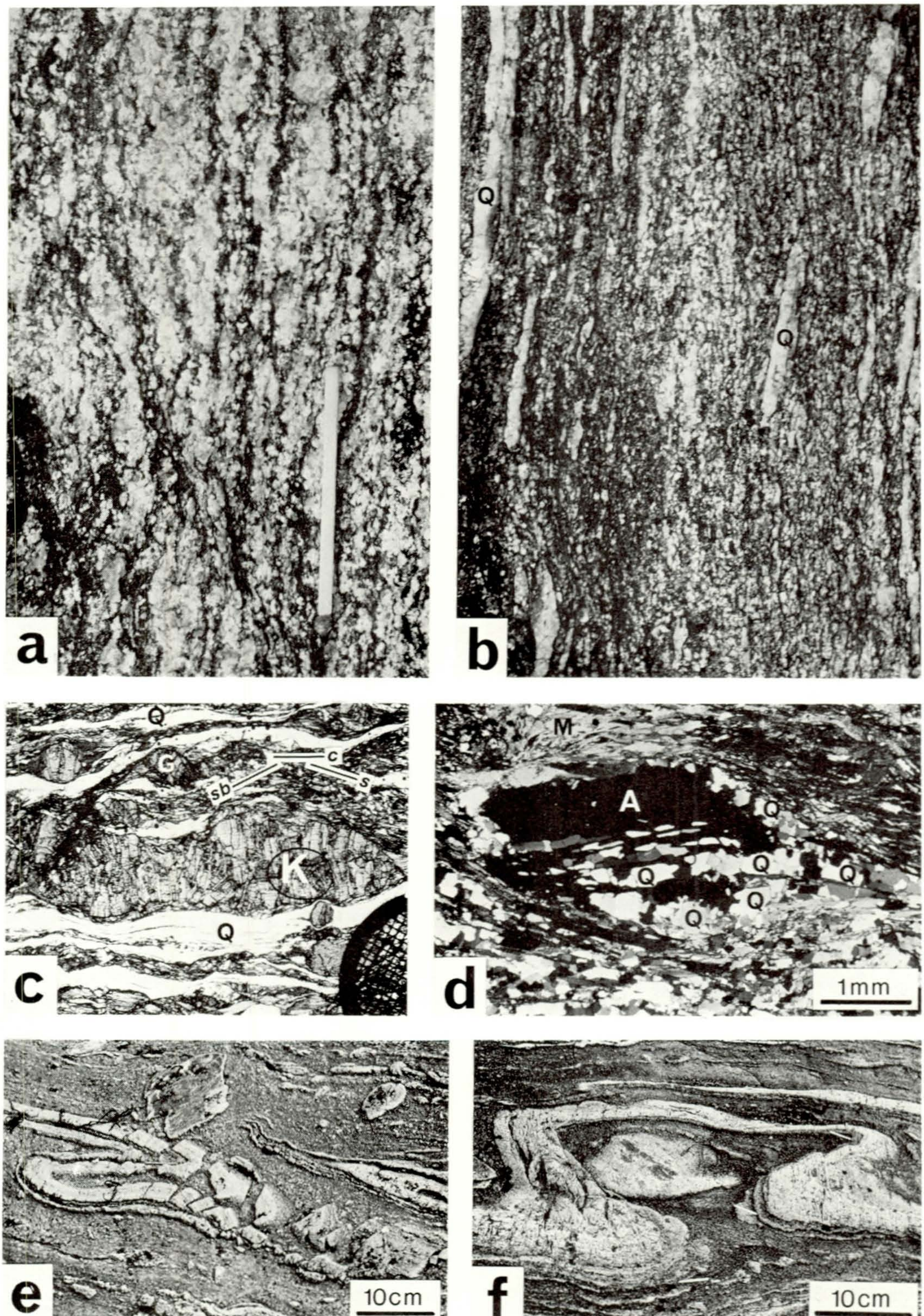
Isotopic dating in shear zones

Once it can be demonstrated that pegmatites or muscovite porphyroblasts in a shear zone are not derived from the protolith but are syn-shearing products, as at Jøssund, where the mylonites are highly muscovitic whereas their protoliths contain no muscovite (p.44 and Figs. 4a & b, 3a), they can be used in attempts at isotopic dating of the time of movement in the shear zone. The Rb-Sr method can be used on muscovite porphyroblasts separated from the pegmatites, or on the micas together with whole-rock samples of their host pegmatite or of the adjacent mylonite (Piasecki & van Breemen 1979, 1983), or together with coexisting feldspar and biotite (see discussion, p.48; see also Cliff et al. 1985). U-Pb methods can be applied to zircon or monazite from the pegmatites (van Breemen et al. 1974, 1978, 1986; van Breemen & Hanmer 1986). The Rb-Sr thin-slab isochron method (Claesson 1980) had also been used to estimate shear-zone ages.

The Western Gneiss Region, north coast of Bjugn

This region of Vestranden has long been known to contain infolds of supracrustal 'cover' metasediments/metavolcanites resting with a tectonic contact on a 'basement' of Proterozoic(?) granitic and migmatitic gneisses (Fig. 1; Wolff 1976, Gee 1978, Dyrelius et al. 1980, Roberts & Wolff 1981). During the present reconnaissance, a part of this area was remapped (Fig. 5; Piasecki 1985). The rocks shown on existing maps as supracrustal metasediments have been separated into: (a) an assemblage of intensely migmatitic paragneisses related to the basement; and (b) a distinct, more weakly migmatised cover succession separated from the gneisses by a major, layer-parallel shear zone (cf. Figs. 1 with 5a & b).

Fig. 3.
(a) Relatively little deformed shear-zone pegmatite with muscovite porphyroblasts (M), in the mylonite of Fig. 4b with muscovitised matrix (Fig. 2d) and with a swarm of quartz plates (right of pegmatite); near locality P in Fig. 5a & 5b.
(b) Quartz plate-pegmatite in a semipelitic mylonite. The mylonite contains small muscovite porphyroblasts (M); quartz - Q, muscovite - M, plagioclase - F; part of the dated pegmatite near Slettliheia (Fig. 7).
(c) 'Early' shear-zone pegmatite, syn-shearing folding and growth of feldspar porphyroblasts. The pegmatite was first deformed with the development of an internal mylonitic fabric (c' in pegmatite); further increments of the shearing movements deformed both into an asymmetric fold, its axial surface corresponding to the S-foliation of the S-C fabric in the host mylonite (s & c). A feldspar porphyroblast (F), overprints the earlier mylonitic C-fabric but later increments of this fabric sweep around it. Other feldspars (F') are indistinguishable from porphyroclasts with tails (see text p.37). All the kinematic indicators (S-C fabric, porphyroclasts with tails, fold vergence), indicate a left-lateral sense of shear transport. Shear-zone separating gneisses from supracrustal metasediments, near Foldereid.
(d) Muscovite porphyroblast (M, 7 mm long) strained and recrystallised, and a plagioclase feldspar (F, bottom) dynamically recrystallised into a granular aggregate (F, centre). Base of the supracrustal assemblage, south Vallersund (Fig. 5).
(e) Shear-zone pegmatite which appears to have nucleated in the S-fabric plane of a mylonite. At (X), the thin pegmatite follows the S-fabric, cutting across the intense mylonitic C-fabric (c) of an earlier phase of the shearing event, without being itself cross-foliated in parallelism with this (c) fabric. At (Y), it has been rotated, evidently during a later increment of shearing into the C-fabric, within which it is drawn out into boudins or 'tectonic fish' (F, enhanced for clarity). The sense of shearing movement is right-lateral. Fleur de Lys Supergroup, Newfoundland, Canada.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The basement assemblage

The most common basement lithologies are granitic *(sensu lato)* gneisses of orthogneiss aspect, commonly with stromatic quartzfeldspathic neosome. They contain isolated pods and trails of separated bodies of amphibolite and other metabasic rocks, and are cut by metabasis dykes apparently absent from the structurally overlying supracrustal succession.

In northern Bjugn (Fig. 5), the granitic gneisses are repeatedly interlayered with a group of coarse paragneisses which are included with the metasedimenary 'cover' on the NGU 1:250,000 map-sheet 'Trondheim' (Wolff 1976). In this work, they are assigned to the basement, because they appear to share the same tectono-metamorphic history as the granitic gneisses. The most common paragneisses are coarse, migmatitic biotite and biotite-hornblende gneisses with stromatic quartz-feldspar neosome (Fig. 4a). Between Lysøysundet and Hellesvika, the hornblende-biotite paragneisses locally becomes very feldspathic and passes into a granodioritic-tonalitic gneiss (nebulite?). From Rømmen to Hellesvika, the biotitic and hornblendic paragneisses are separated by a mappable unit of a psammitic paragneiss which contains boudins of amphibolite and calc-silicate gneisses. These paragneisses have been traced northeast to Åfjord, and Roberts (1986) has recorded the presence of apparently similar paragneisses further north within Vestranden.

The contacts between the granitic orthogneisses and the paragneisses are usually followed by minor, layer-parallel zones of particularly high strain, generally no more than a few metres thick (X in Fig. 5b). Similar zones, but op to 20 m thick, are developed along the boundaries between the different paragneiss lithologies, and seem to anastomose on the regional scale. Since these zones contain muscovitised protomylonites and mylonites (Fig. 2d & 4b), with macro- and microscopic S-C foliations, shear bands, swarms of quartz plates (Figs. 2b & 4b) and shear-zone pegmatites (Figs. 3a, 6, p. 37), they are taken to represent minor shear zones. At Lysøysundet and at Jøssund (p. 44), S-C foliations and shear bands in these minor shear zones indicate an apparent sense of left-lateral strike-slip shear movement (hanging wall to the southwest). However, subsequent to the shearing, the rocks have been folded by upright NE-SW trending folds. In the opposite limbs of these folds the sense of shearing becomes reversed, and in many rocks only an *apparent* sense of shear (to the SW or NE) can be derived. A distinctive feature of all the basement rocks is that they contain only minor shear zones, in between which there are large areas of untectonised gneisses. By way of contrast, the cover rocks are more intensely sheared, containing wide zones of mylonites and protomylonites.

The supracrustal cover assemblage

In contrast with the basement paragneisses, the cover metasediments are more weakly migmatised calc-schists and calc-psammites with developments of lenticular marbles and calc-silicate rocks at their structural base.

Fig. 4.
(a & b) Rocks from the dated minor shear-zone at Jøssund (P' in Fig. 5). Both natural size. Both share the same major and trace element composition.
(a) Semipelitic, migmatitic biotite-paragneiss, with abundant stromatic neosome (coarse white), just outside the shear zone.
(b) A mylonite derived from the paragneiss of Fig. 4a. The coarse neosome has been granulated, dynamically recrystallised and has merged into the groundmass, which is strongly muscovitised (Fig. 2d); the protolith contains no muscovite. The quartz plates (Q) and muscovite-pegmatites (Figs. 2f, 3a) which characterise the sheared rocks are not present in the parent paragneiss.
(c) Relics of a higher-grade paragenesis preserved as porphyroclasts (*sensu stricto*) in blastomylonite derived from supracrustal metasediment. Quartz plates (Q) in the C-mylonite fabric plane surround a deformed kyanite (K), whereas a garnet (G) in a micaceous stringer is deformed by a shear band. S-C foliations (s & c) and shear bands (sb) indicate a left-lateral sense of movement. Shear-zone at the base of the supracrustal assemblage, north-eastern extremity of Vallersund in Fig. 5. The circular grid is 3 mm in diameter.
(d) A syn-shearing albite porphyroblast (A, black). It had overgrown earlier elements of a shear fabric (the included quartz plates, Q'), but has been augened during continued shearing, the fabric of which sweeps around it (quartz plate (Q) at its top right and the mylonitic schistosity). Fleur de Lys Supergroup, Newfoundland, Canada.
(e, f) Structures in mylonites derived from marbles:
(e) 'Early' asymmetric fold of a calc-silicate layer in marble, broken and drawn out by later extensional movement; rotated blocks above fold. Vallen (Fig. 5).
(f) Sheat fold in calc-silicate layer within marble. Vallen.

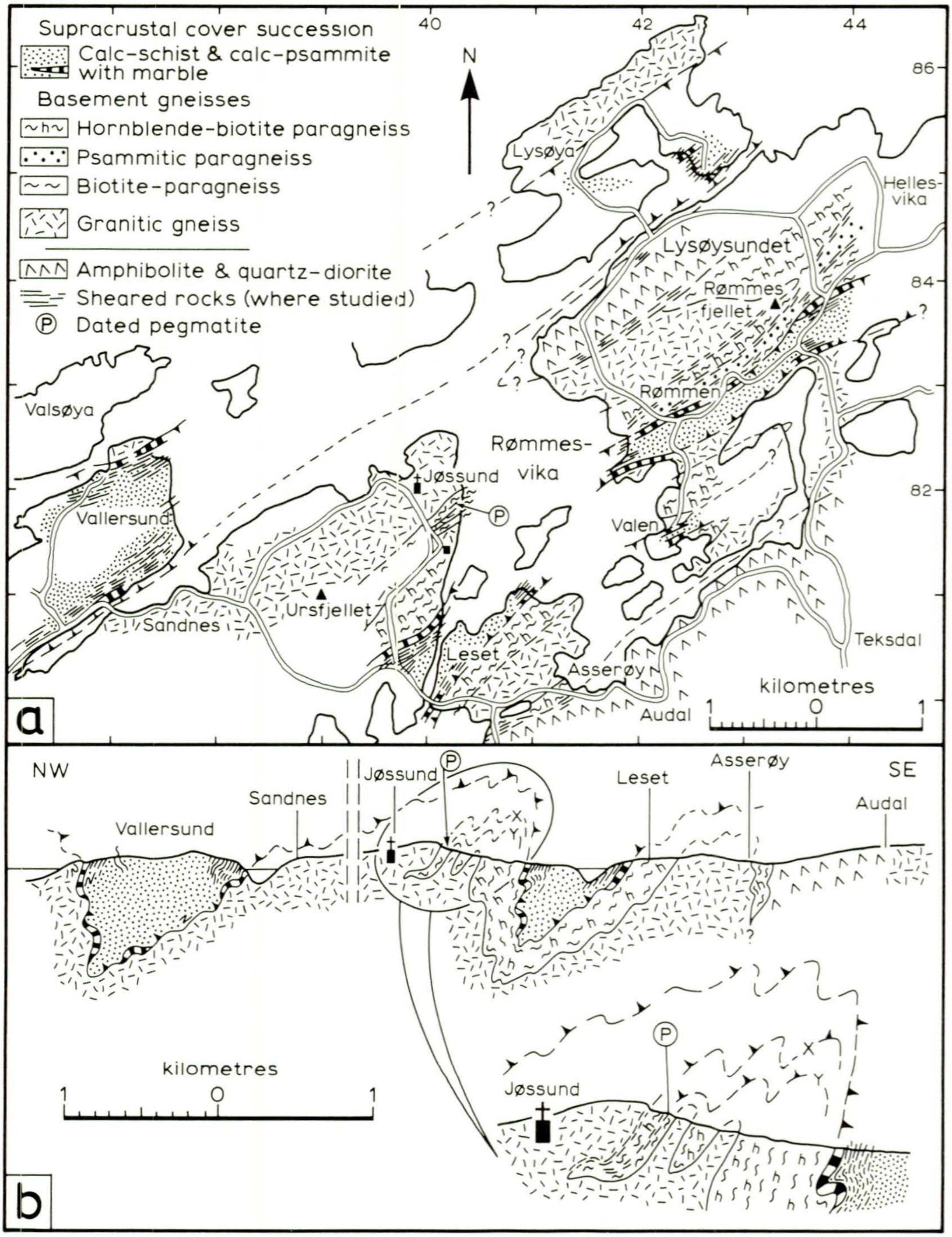

Fig. 5.
(a) Provisional geology of a part of the northern coast of Bjugn, based on reconnaissance mapping. Fig. 1 shows the geology of the same area after the NGU 1—250,000 map-sheet Trondheim' (Wolff 1976).
(b) Generalised section showing interfolded granitic gneisses and paragneisses in the basement complex, the minor shear-zones in the basement (X and Y in the inset), and the related major thrust at the base of the supracrustal assemblage, all modified by the late, steeply inclined NE-SW trending folds, such as the Vallersund synform. Minor syn-shearing folds are shown diagrammatically, folded by the Vallersund synform.

They also contain developments of:

(a) Highly garnetiferous, pelitic biotite-amphibole schists, commonly with disseminated sulphides.

(b) Regularly banded amphibolites.

(c) Massive, garnetiferous amphibolites.

(d) Trails of boudins (dykes?) of garnetiferous amphibolite.

(e) Trails of boudins of retrogressed eclogitic rocks.

The presence of retrogressed eclogitic pods, as at Jøssund-straumen, and of a mylonitic kyanite-garnet schist (Fig. 4c) with retrogressed relics of very coarse brown amphibole and amphibolitised clinopyroxene indicate retrogression from an earlier, higher grade metamorphic assemblage, possibly of granulite facies. This observation is consistent with the local preservation of granulite facies assemblages in apparently similar metasediments at Roan (Möller 1986). Thus, in terms of lithologies, apparent metamorphic history and tectonic relationship with basement gneisses, the supracrustal rocks of north Bjugn can be reasonably well correlated with the supracrustals of Åfjord and Roan, and possibly also with those at Foldereid (inset in Fig. 1; for descriptions of the rocks see Möller 1986, Schouenborg 1986).

Major shear zone at the gneiss — supracrustal cover boundary

This boundary is marked by a spectacular zone of shearing in which the supracrustal rocks are variably mylonitised for up to 300 m from the contact, and the gneisses for up to 50 m. The zones of highest shear-strain are marked by belts of mylonites and ultramylonites which anastomose around elongate lenticles or 'augen' of less stained protomylonites and blastomylonites. The mylonitic foliation follows the plane of the lithological layering of the metasediments, intensifying their preexisting schistosity, and overprinting the initially higher grade assemblages in the rocks (Fig. 4c). This layer-parallel shearing was accompanied by the growth of mid-amphibolite facies minerals such as muscovite, biotite, plagioclase (An_{29-32}) and locally sillimanite (fibrolite). In CaO-rich rocks, quartz plates and small shear-zone pegmatites carry large porphyroblasts of carbonates, as well as epidote and amphibole in calc-silicate rocks rich in Al_2O_3, MgO and FeO. Pelitic mylonites contain porphyroblasts of muscovite, generally strained and recrystallised (Fig. 3d), indicating either one extended phase of shearing, or at least two distinct shearing events. Mineral stretching lineations related to the shearing, generally better developed in the granitic gneisses than in the less competent supracrustals, trend NE-SW, perpendicular to the ESE stretching direction typical of Caledonide nappes to the east of the Western Gneiss Region. In common with the minor shear zones in the basement gneisses, S-C and shear-band foliations in the cover rocks indicate an apparent sense of movement in which the hanging-wall was transported to the southwest. The oblate shapes of many fabric elements, the flattened aspect of asymmetric folds, and the common presence of very low-angle S-C fabrics, indicate a strong flattening strain in the shear zone.

The most common folds within the zone of shearing are minor syn-shearing structures which fold earlier mylonitic fabrics, whilst later increments of this fabric form their axial surface foliation (Fig. 6). They are commonly curvilinear, with hinges rotated towards parallelism with the regional stretching lineation: and in some places in the marbles and calc-silicate rocks they grade into sheath folds (Fig. 4f). There may be several sets of these folds, suggesting an episodic nature for the thrusting movements.

The marble in contact with the gneisses has been so intensely strained and mobilised that locally it transported almost undeformed blocks of gneiss, and has been injected into small anastomosing shear zones in the basement. Following the shearing movements, the marble had recrystallised to a coarse granular texture. Only disrupted layers of amphibolite, calc-schist and calc-silicate ribs preserve fabric relics of the shearing, in the form of asymmetric folds (Fig. 4e), sheath folds (Fig. 4f), asymmetric boudins, rotated blocks of calc-silicate rock (Fig. 4e) and rotated porphyroclasts of feldspar and garnet. The marble also displays evidence of a multiphase, probably prolonged shearing history. Its calc-silicate boudins (some containing earlier formed, internal, ductile boudinage structures) were first rotated and stacked (imbricated) by compressional movements which probably also formed the asymmetrical folds; following which, at least some boudins were pulled apart by

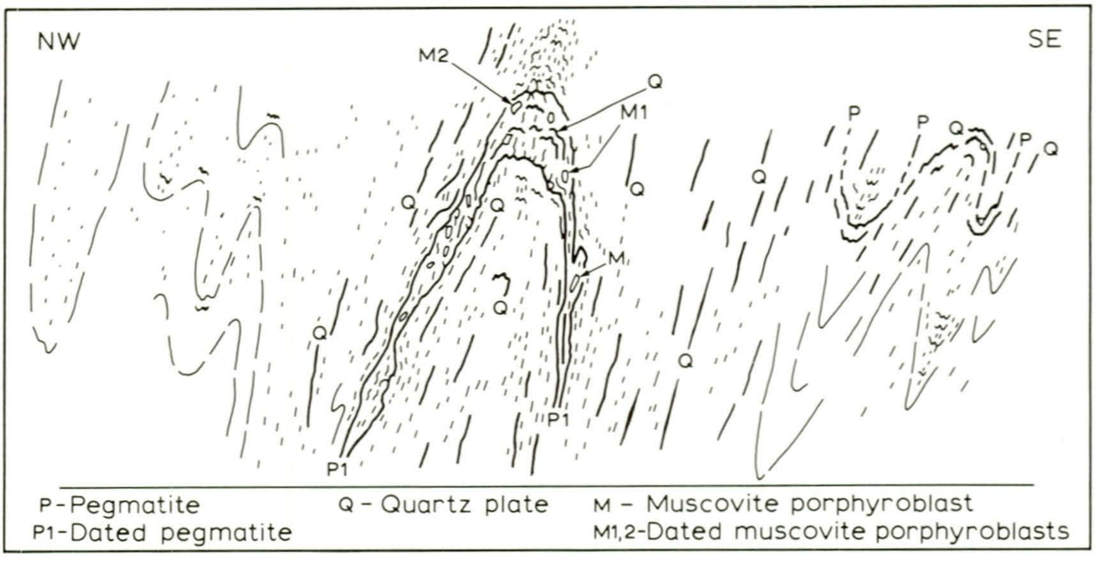

Fig. 6. Dated pegmatite in the minor shear-zone at Jøssund. Sketch of the dated pegmatite (P in shear-zone Y in Fig. 5b), showing the locations of the dated muscovite porphyroblasts. Syn-shearing folds deform the earlier shear fabric (crenulated schistosity, quartz plates (Q) and the pegmatite itself), while their axial surfaces are defined by later increments of this fabric - a mylonitic foliation and later quartz plates (Q). The steep attitude of the shear fabric is caused by the late, upright folds, trending NE-SW.

more brittle extensional movement (Fig. 4e). All these kinematic markers consistently indicate an apparent sense of shear transport in which the hanging-wall appears to have moved towards the southwest, along the trend of the regional stretching lineation.

The shear zone has been subsequently deformed by open, near-upright folds which trend NE-SW and range from minor structures to major folds responsible for the repetition of the cover-basement outcrop pattern (Fig. 5a & b). Identical, late upright folds are also extensively developed in the Vestranden region to the north of Bjugn (e.g. Roberts 1986).

The initial attitude of the shear zone is more difficult to assess. However, Fig. 5b indicates that the major upright folds deform a regional layering which, prior to this folding, appears to have been subhorizontal to gently inclined. The time interval between the shearing and the upright folding was probably relatively short (p. 48), and this 'flat' attitude is thought to represent the initial attitude of the shear zone.

Minor shear zone at Jøssund

From Jøssund to Lysøysundet, the contact between the biotite paragneisses and the hornblende-biotite paragneisses is followed by a minor shear zone (P, and Y in Figs. 5 & 5b). This and other small shear zones in the paragneisses (p.41) are thought to be related to the major thrust at the base of the cover succession; they are subparallel to it, and their kinematic indicators indicate the same apparent sense of movement. They probably represent local imbricate structures in its footwall (Fig. 5b).

At Jøssund, the coarse biotite paragneiss contains quartzofeldspathic leucosomes bounded by biotitic selvages, and is free of muscovite (Fig. 4a). As this paragneiss is traced into the shear zone, it gradually becomes proto- and blasto-mylonitic, and its matrix biotite becomes replaced by muscovite (Fig. 2d). Its migmatitic quartz-feldspar leucosome becomes recrystallised and merges into the groundmass, and swarms of quartz plates ranging in size from microscopic to 0.5 m in length form in the resultant mylonitic rock (Figs. 4a & 4b). This mylonitic zone also contains a swarm of typical shear-zone pegmatites, some of which are quartz plate-muscovite pegmatites (Fig. 2f), while others contain feldspar. They vary from highly foliated, lenticular bodies, some folded by syn-shearing folds (Fig. 6) and probably related to an earlier stage of the shearing movement, to less deformed pegmatites (Fig. 3a), of a later stage in the same(?) shearing episode. Significantly, no muscovite-bearing pegmatites have been found in the well exposed paragneisses outside the shear zone.

Caledonian Nappes, Leksvik

Southeast of the Verran Fault (Rindstad & Grønlie 1986), a prominent belt of complex, ductile-to-brittle faulting, the metasediments and metavolcanites assigned to the Støren and Gula Nappes (Roberts & Wolff (1981) or the Seve Nappes (Gee 1978), surround tectonic windows of basement gneisses at Buan, Storvatnet and to the north of Store Juvatnet (Fig. 1). The basement-cover boundaries are generally subhorizontal to gently inclined, and are followed by zones of layer-parallel ductile shearing up to 700m thick.

Basal shear zone, Store Juvatnet

North of Store Juvatnet, in the area of Fig. 7, a thick, gently inclined zone of layer-parallel shearing follows the basement-cover boundary. Along this boundary, at least 50m of granitic basement gneiss has been converted to fine-grained mylonites and ultramylonites. This mylonitic gneiss contains slices of cover-derived mylonites which have been subsequently broken up into blocks and rotated, with the apparent sense of movement being that of subhorizontal overthrusting towards the southwest.

For tens of metres above the basement, many cover derived phyllonites (phyllosilicate mylonites) consist, by volume, of 20—40% of quartz plates. They are strongly retrogressed to greenschist assemblages, with pronounced chloritisation of garnet and biotite and epidotisation of plagioclase. Muscovite-rich patches, some representing relics of muscovite porphyroblasts recrystallised to fine-grained aggregates of mica, are bounded by late-formed S-C foliations and shear bands, giving the phyllonites the appearance of 'button schists'. The S-C fabrics, shear bands and occasional rotated porphyroclasts of retrogressed garnet and feldspar, indicate apparent overthrusting towards the southwest. The rocks have also been deformed by very late, minor conjugate folds, which verge SE and NW, and probably relate to movements on the Verran Fault.

The structurally lowest supracrustal formation surrounding this window of gneiss is not the same calcareous semipelite that extends from Store Juvatnet to Olsøya and Storvatnet (cf. NGU 1:50,000 preliminary map-sheet 'Leksvik', Wolff 1973), but a thick, aluminous, garnet-semipelite which also contains amphibolites and a psammitic horizon (Fig. 7).

The mylonitic zone and pegmatites of Slettliheia

For some 700m above the contact with the basement gneiss, the cover metasediments and amphibolites are very strongly tectonised, with developments of intense mylonitic fabrics in zones of highest strain which appear to anastomose on the regional scale. The mylonitic rocks contain pervasive matrix muscovitisation, swarms of quartz plates, small shear-zone pegmatites and local developments of muscovite porphyroblasts.

Further above the thick basal shear zone, zones of very high strain are more sporadically distributed. South of the prominent amphibolite which trends towards the summit of Slettliheia, a 100m-wide zone of particularly well developed mylonites with abundant quartz plates (Fig. 2a) contains a swarm of shear-zone pegmatites (P in Fig. 7). In the mylonites of this zone, the intensity of muscovitisation of matrix biotite appears to be proportional to the number of quartz plates developed in the rock. Likewise, the frequency of occurrence and the size of muscovite porphyroblasts in the mylonites is also related spatially to the quartz plates and pegmatites, indicating that all these products represent strain-induced segregations within the shear zone.

The pegmatites vary from drawn-out lenticles so highly deformed that they may be mistaken for psammitic mylonites, to later, quartz plate-pegmatites, necked and boudined but internally much less deformed, such as the pegmatite selected for dating (Fig. 3b). In this zone, late, layer-parellel shearing movements which appear to have been subsequent to the formation of the pegmatites were accompanied by retrogressive, greenschist facies metamorphic conditions. They resulted in the formation of S-C foliations and shear-bands and in the displacement of boudins, again indicating an apparent sense of overthrusting movements

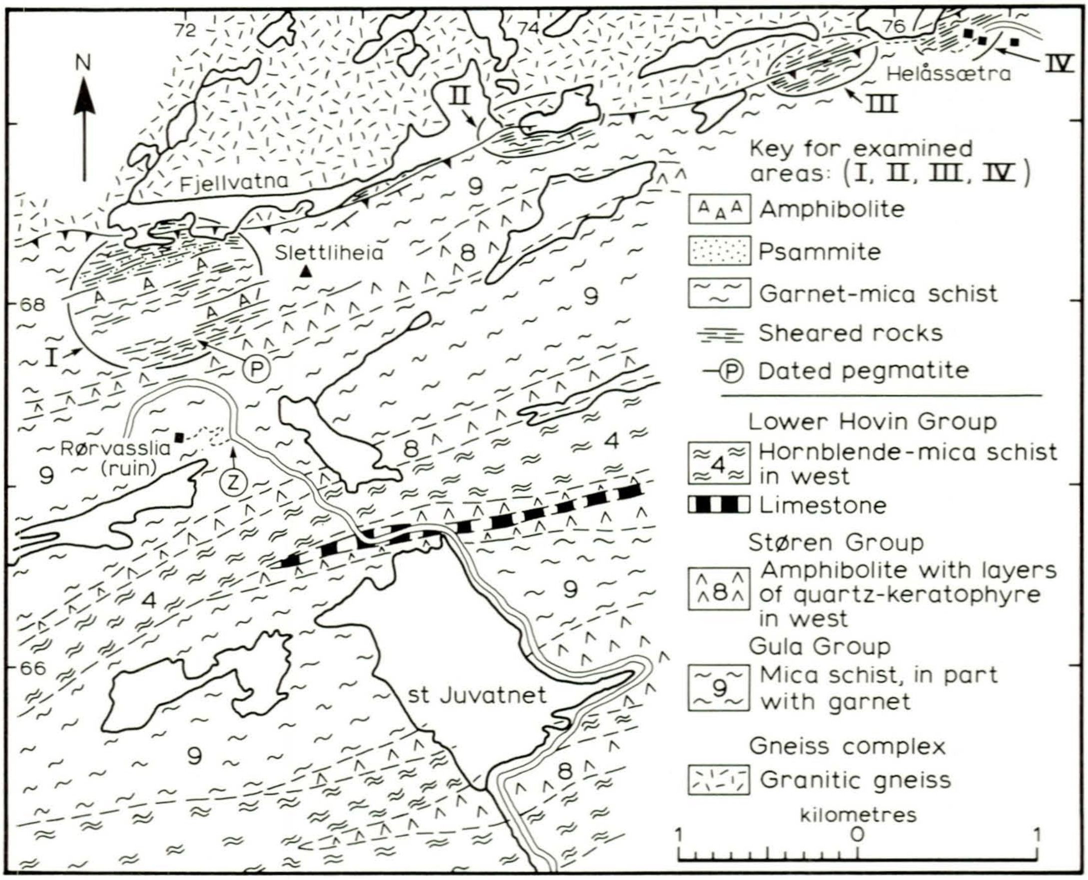

Fig. 7. Outline geological map of the Store Juvatnet area. Geology after the NGU 1:50,000 preliminary map-sheet 'Leksvik' (Wolff 1973), except in the studied areas (circled). The symbol for sheared rocks relates only to examined exposures.

towards the southwest, along the direction of a commonly developed stretching lineation. These late effects appear to have obliterated many earlier fabrics in the rocks, all the recorded kinematic indicators apparently relating only to the late movements.

New isotopic data

Rb-Sr analytical procedure

From muscovite porphyroblasts, approximately lgm was extracted from the freshest and least strained part of the cores of the porphyroblasts. Matrix micas were separated using conventional magnetic and heavy liquid procedures and purified by prolonged grinding under methanol in an agate mortar. In each case, between 0.1 and 0.2 gm was weighed for analyses. Rb and Sr were separated by standard cation-exchange methods. Rb isotope dilution measurements were made in triple tantalum filaments; replicate analyses of unspiked Rb, separated using the normal procedures, show that this method yields isotopic compositions that are reproducible to within 0.7% at the 95% confidence level. Rb/Sr ratio determinations are referred to a mixed ^{87}Rb-^{84}Sr spike calibrated against gravimetric standards and checked against replicate analyses of SRM 607 K-feldspar, which gave model ages within 0.6% of the certificate value of this standard. The reproducibility of strontium isotopic compositions was monitored using

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Age (ma)
Shear-zone in the Central Gneiss Region, Jøssund:					
Pegmatite:					
1. muscovite porphyroblast M1*	320	70.4	13.25	0.79579	389 ± 6
	308	68.0	13.18	0.79436	388 ± 6
2. muscovite porphyroblast M2*	310	69.1	13.12	0.79373	386 ± 6
	310	69.2	13.09	0.79391	388 ± 6
3. plagioclase	7.63	453	0.0488	0.72227	
Mylonite:					
4. matrix muscovite*	255	60.2	12.32	0.78792	379 ± 6
	249	57.7	12.56	0.78886	377 ± 6
5. matrix biotite*	455	11.7	119.1	1.3425	366 ± 5
	440	16.8	79.11	1.1324	365 ± 5
6. plagioclase	9.82	178.4	0.1595	0.72234	
Shear-zone near St. Juvatnet (Slettliheia)					
7. Pegmatite muscovite porphyroblast*	710	5.39	491.5	3.6918	424 ± 6
	771	5.12	586.0	4.2503	422 ± 6
8. Pegmatite plagioclase	22.2	360	0.1788	0.71970	

TABLE 1. Rb-Sr data for shear-zone pegmatites. *denotes duplicate analyses of the same sample.

SRM 987, which gave a mean of 0.71029 ± 0.00003 over the period of the analyses presented here. Analytical uncertainties in the calculated ages, estimated by a combination of the uncertainties in mass spectrometry and spike calibration, amount to $<$1.5% at the 95% confidence level.

Analytical results

Results for samples collected from the Jøssund and Slettliheia shear zones are given in Table 1. In each case all of the principal Rb-Sr-bearing minerals were analysed. Mica ages were calculated using co-exisiting feldspar as control on the initial ratio.

Jøssund shear zone. In the minor shear zone at Jøssund (p. 44), a quartz plate-pegmatite bearing large 'books' of muscovite and folded by syn-shearing folds (Fig. 6) was selected for isotopic dating. In this pegmatite, in the lower strain region of the fold hinge zone, muscovite porphyroblasts were relatively little deformed and not recrystallised. The following samples were analysed (Table 1):

(a) From the pegmatite, two of the least deformed muscovite porphyroblasts measuring 5 cm across (001) and more than 1cm thick (samples 1 and 2 in Table 1, and *shown as M1 and M2 in Fig. 6).*

(b) From the host mylonite, samples 4 & 5 are, respectively, small matrix muscovite grains believed to have formed by replacement of biotite during the shearing (Fig. 2d), and small grains of matrix biotite thought to represent biotite of the protolith recrystallised during the shearing.

(c) Samples 3 and 6 are plagioclase feldspar from the pegmatite and the host mylonite (An_{32} and An_{28-32}, respectively), for use as a control on the initial $^{87}Sr/^{86}Sr$ ratio together with the other samples.

The central cores of the two large muscovite porphyroblasts yielded ages within the narrow range of 389 to 386 ± 6 Ma; the matrix-sized muscovite gave an age of 378 ± 6 Ma (averaged), and biotite and age of 365.5 ± 5 Ma.

Store Juvatnet (Slettliheia) shear zone. From this mylonitic zone (p. 45), a large muscovite porphyroblast (sample 7), 5 cm across (001) and 3 cm thick, and a plagioclase feldspar (albite-oligoclase, sample 8) were selected from a boudined quartz plate-pegmatite of the less deformed type (Fig. 3b located at P in Fig. 7). The muscovite was weakly strained around its margins, and the undeformed part of its central core yielded an age of 423 ± 6 Ma (averaged age, Table 1).

Discussion of results

The pegmatite dated at Jøssund can be shown to be syntectonic with the shearing movements within the basement paragneisses, and also with the movements in the major shear zone developed along the basement-cover boundary in northern Bjugn (pp. 44 and 43). Thus, the ages obtained from the Jøssund pegmatite and its host mylonite relate to the strain-induced formation of the pegmatite during the shearing event, and to the subsequent thermal history of the minor and major shear zones.

The *c.*389 Ma (Early to Middle Devonian) age obtained from the undeformed cores of large muscovites from the pegmatite at Jøssund, may be interpreted as:

(a) A cooling age, related to the uplift of a pegmatite formed during an old (Scandian?) shearing event;

(b) A reset value, representing the formation of the pegmatite during an old shearing event, but reset during a Devonian reactivation of the pre-existing shear zone; or

(c) The formation of the pegmatite during an Early to Middle Devonian shearing event.

The first two alternatives are not favoured, because of observations that, in muscovite, the effective grain-size for diffusion appears to be closely related to the actual grain size: so that, in large pegmatitic muscovite 'books', closure temperatures for Sr diffusion appear to be substantially higher than in normal matrix-size grains (eg. Fig. 2d), and may be as high as c. 650°C (for a review of the closure temperature concent see Cliff 1985). For example, in Scotland, old shear zones have been involved in Early Palaeozoic, medium- to high-grade, amphibolite facies metamorphism and reworking. However, a well defined pattern of isotopic ages relating to the old shearing event has been retained in those large, pegmatitic muscovite books which subsequently have been least deformed. One such large muscovite book has been shown to preserve an age gradient normal to its grain boundaries (van Breemen et al. 1974, 1978, Piasecki & van Breemen 1983 and unpublished work).

Thus, the *c.*389 Ma age from the pegmatitic muscovites at Jøssund is interpreted as representing a time close to the formation of the pegmatite, and close to the movements in the minor shear zone within the Jøssund paragneisses. This implies that the related major shear zone developed along the basement-cover interface is of the same age; or, that it contains a Devonian component of movement so intense that it had obliterated any older shear fabrics that may have been present.

The c.378 Ma and 365 Ma (Middle and Late Devonian) ages of the small matrix micas from the mylonite which hosts the Jøssund pegmatite, are interepreted as relating to regional uplift and cooling through *c.*500°C and *c.* 300°C, the estimated closure temperatures for Sr diffusion in small grains of muscovite and biotite, respectively (Purdy & Jäger 1976, Cliff 1985).

The 422—424 Ma ages obtained from the central core of the large muscovite book from the Slettliheia pegmatite is interpreted as representing the approximate time of formation of the pegmatite, apparently corresponding with Scandian thrusting. As could be expected from experience with similar material from Scotland, the later event of shearing associated with retrogression appears to have had little effect on the Rb-Sr system in the central core of the large muscovite. This late event, with its southwesterly sense of tectonic transport, similar to the sense of transport at Jøssund, is also likely to have been of Devonian age. Because of the overprinting nature of this event, the sense of movement during the earlier, 422—424 Ma shearing and the grade of its accompanying metamorphism are not known.

Summary and conclusions

The data presented here indicate that the rocks of this Vestranden part of the Western Gneiss Region have been affected by a major event of layer-parallel ductile shearing which appears to be of Early to Middle Devonian age (*c.*389 Ma). These movements, accompanied by medium-grade amphibolite facies metamorphism, have modified and retrogressed basement gneisses and supracrustal cover metasediments previously metamorphosed at a higher grade (p. 43) and correlatable with the granulite facies basement and cover rocks in the nearby Roan area (Möller 1986). This higher grade event may correspond to either the Scandian or a pre-Scandian high-T/P metamorphism (Dallmeyer & Gee 1986); a third alternative is that it may be Proterozoic.

The Early to Middle Devonian (c.389 Ma) shearing probably occurred during regional uplift and cooling of the Vestranden region, which appears to have reached the *c*.500°C and *c*.300°C thresholds at approximately 378 and 365 Ma (Middle and Late Devonian). At some stage after the *c*.389 Ma shearing, the region was deformed by major and minor upright folds on a NE-SW trend. This folding could broadly correspond with the folding and low-grade metamorphism within the Devonian sedimentary basins of Fosen (Fig. 1), Hitra (Roberts & Sturt 1980, Roberts 1983), and at Kvamshesten, where Middle Devonian clastics have been affected by polyphase deformation including near-isoclinal folding of probable Late Devonian - Early Carboniferous age (Torsvik et al. 1987).

The *c*.389 Ma shearing event is unusual, in that its stretching lineation trends NE-SW, at a high angle to the usual trend of the shearing-related lineation in adjacent regions. Likewise, kinematic indicators point to a direction of transport *not* towards the east or southeast, but parallel to the axial trend of the Caledonide orogen. In Bjugn, the attitude of the shear zone was probably subhorizontal (p. 44), with a sense of overthrusting movement to the southwest. At Leksvik, a subhorizontal to gently inclined, *c*.423 Ma (Scandian) thrust zone has been reactivated, again with an orogen-parallel direction of transport, probably also in Devonian time. In these regions, separated by the Verran Fault and at least one major ductile shear zone (east of Botngård), the metamorphic grade accompanying the shearing varied from amphibolite to greenschist facies.

If this late, orogen-parallel, shearing event has been widespread, then its fabrics can be expected to overprint the fabrics of any earlier, southeast-directed shearing; and to test this, more field data are required. A NW-SE trending lineation has been observed immediately north of Bjugn, in Roan, and an irregular lineation in the Namsos area (Roberts 1986, Möller, pers. comm. 1986). In the area of Fig. 5, where the orogen-parallel shear fabric is intense, earlier fabrics indicating southeasterly directed transport have not been seen during this reconnaissance.

Regionally developed shearing with an orogen-parallel sense of transport is of widespread occurrence in the Gander Terrane of Newfoundland, where it takes the form of wide belts of (Acadian?) subhorizontal overthrusting and of vertical strike-slip movements (Hanmer 1981, Piasecki 1988). In Vestranden, the regional distribution and the significance of the c. 389 Ma, orogen-parallel, originally probably subhorizontal shearing event are not clear. Its presence appears to indicate that at least part of the Western Gneiss Region in Nord Trøndelag may constitute a terrane tectonically different from the rest of the central Scandinavian Caledonides.

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