The Northern Kongsberg Series and its Western Margin

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In the Kongsberg Series a major fold interference pattern was established during the Svecofennian orogeny before westward thrusting over the Telemark block developed a margin of ultramylonite (preserved from Flesberg to lake Soneren): further north (to Ådal) this was cut out by a later mylonite. A subsequent, basic intrusive phase was associated with rifting, which was aborted by the onset of the Sveconorwegian (Grenvillian) Regeneration. Late reactivations of the whole margin caused brittle faulting and developed the so-called 'friction breccia'. The early regional structure and its relics could explain many features of the Kongsberg Series; in particular, the Modum area complex may represent Bamble Series rocks infolded into the Kongsberg Series during the Svecofennian orogeny.

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Introduction

The northern part of the Kongsberg Series (Fig. 1) presents a number of problems related to the subdivision of the southern Fennoscandian Shield. The Geological Map of Norway (Holtedahl & Dons 1960) shows the Kongsberg Series with a north-south lithobanding and a western junction against the Telemark Series, marked by a fault or breccia line. This 'friction breccia' (of Bugge 1928) trends north from Kongsberg (Fig. 1) for about 50 km, bends at Haugesjø and runs northeast for some 60 km, disappearing at Sokna, where the Kongsberg and Telemark Series merge. Smithson (1963) showed it continued north of Sokna, splitting towards the Flå (Ådal) granite, but he commented that 'the rocks are similar on both sides of the fault'. Recently, Hageskov (1979, 1980) has suggested it might continue north of the Flå granite around Bagn. Additional problems are associated with the occurrence, in the centre of the northern Kongsberg Series, of a 'Modum area' subdivision containing very different lithologies.

The present study concentrates on the western part of the Kongsberg Series, north of Haugesjø, and the geology of the Series from its margin eastwards to the Modum area complex. It covers a tract north of the Flesberg area of Bugge (1937) and west of the Modum district of Jøsang (1966). Summary results of a regional reconnaissance and tectonic synthesis (Fig. 1) cover a wide area including the Modum district and the tract northwest of Tyrifjorden studied by Hofseth (1942): the southern margin was included on the 1:250,000 map sheet 'Skien' (Dons & Jorde 1978) and the northern margin was covered by Smithson (1963) in his study of the Flå granite (comprising the Ådal granite and a more northerly Hedal granite).

Cataclastic rocks are described using the lithological nomenclature of Higgins

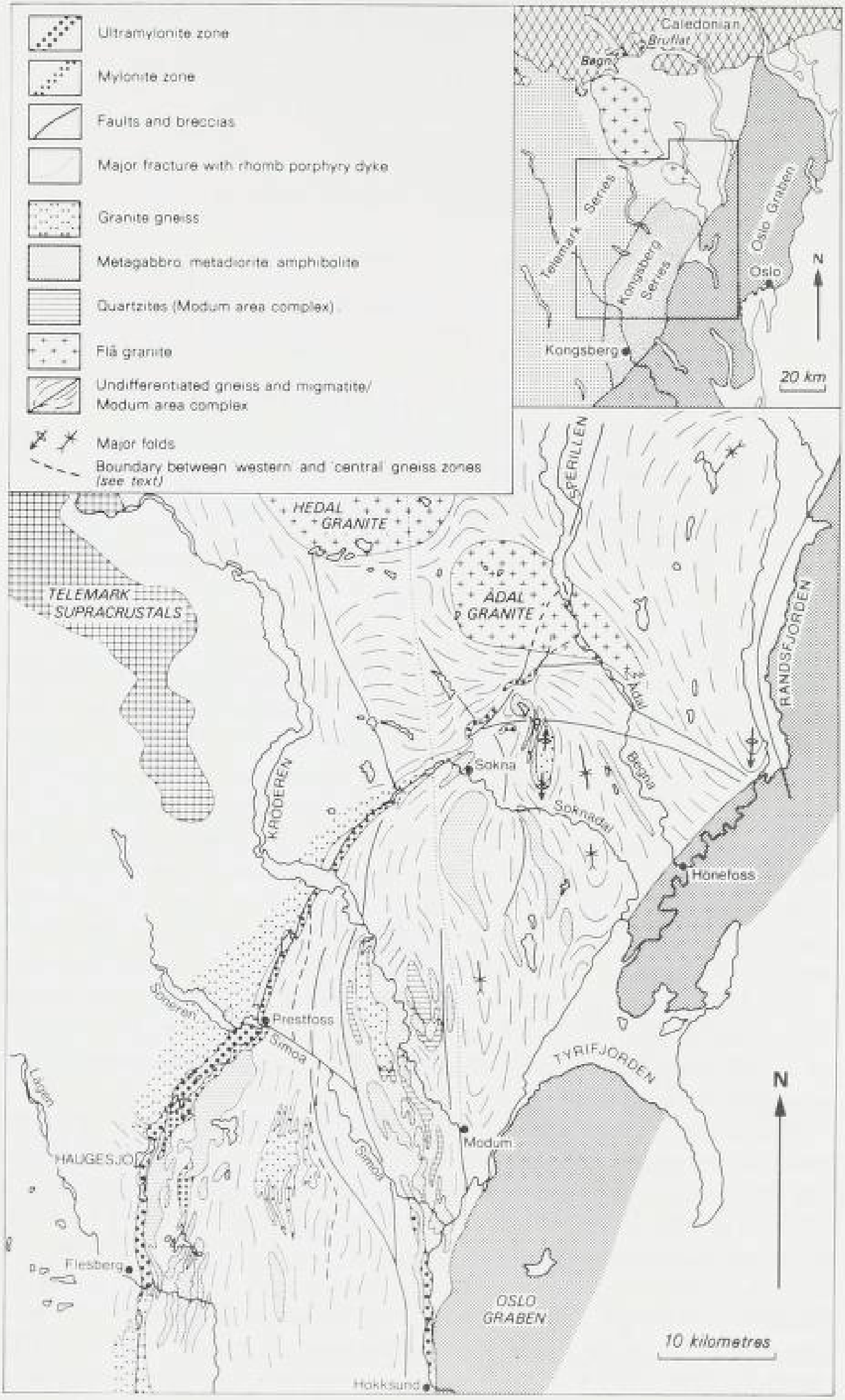

Fig. 1. General geology of the region. The boundaries of the Ådal granite are taken from Smithson (1963) and the geology of the Modum area from Jøsang (1966).

(1971). In terms of the nomenclature of Zeck (1974) they show some myloblastic recrystallisation (synchronous with cataclasis) and dominant blastomylonitic recrystallisation (after cataclasis).

Regional geology of the northern Kongsberg Series

A north-south lithobanding and foliation in the west results from cataclasis. Eastwards, a few remnants of early fold closures are preserved, although the tectonic pattern becomes less ordered around the later basic intrusives and Flå granites. Several closures, apparent on a regional scale (Fig. 1), are seemingly remnants of a 'closed' interference pattern, broadly conforming to the 'dome and basin' type. The structures are difficult to distinguish, due to original complexities, steep foliations, transposition and later folding. Smaller major structures are sporadically preserved (e.g. the granitic dome, east of Sokna, Figs. 1, 4 & 5), as are related minor folds.

The complexity of the elongate domes and basins was partly due to their development from the interference of three fold phases. They were elongated with steep N to NNW striking axial planes (with some axial planar foliation and transposition at their hinges). Associated tight to subisoclinal minor folds showed some transposition and syntectonic garnet growths. They refolded an earlier foliation with a few minor isoclines, which were often intrafolial. A third fold phase produced open to tight, minor flexures, with steep ENE to NE axial planes. All these deformations interacted to produce a major interference pattern (referred to as 'the early regional structure' in the present study) and developed prior to the intrusion of gabbros and the cataclasis associated with the western mylonite zones. The interference patterns were, therefore, much older than the late concentric folding, which was dominant in the Telemark Series and in the western Kongsberg Series.

LITHOLOGICAL DISTINCTIONS BETWEEN MAJOR STRUCTURES

There is some lithological distinction between rocks of the individual major structures. West from Randsfjorden to the Flå granites (Fig. 1), the rocks are heavily migmatised gneisses with amphibolites and some protomylonites. They generally have shallower dips than the Kongsberg Series to the southwest, and are severely affected by open flexuring (and some doming) related to the late concentric folding. One shallow, major synform west of Randsfjorden (in the northeast of Fig. 1) could reflect this later folding.

The southward synformal closure at the north end of Tyrifjorden (and its continuation through Soknadal) occurs in plagioclase–quartz–biotite gneisses and schists (± garnet and muscovite) with some biotitic, graphitic and sulphidic schists, thin quartzites and thin amphibolites. In the west of this structure, about 10 km west of Hønefoss and just south of Soknadal, Hofseth (1942) recorded the development of sillimanite gneisses. The other structures closing along the northwest of Tyrifjorden (Fig. 1) occur in a mixed series of garnetiferous biotite–plagioclase–quartz gneisses, hornblende-rich gneisses and abundant amphibolites.

To the west, the location of the Modum complex correlates with the regional fold pattern and is discussed below. Further west, in the area of the detailed survey (Figs. 2–5) another different series of gneisses and protomylonites (towards the western ultramylonite) have a general north-south banding and have been divided into a 'western' and 'central' zone (Figs. 1 & 2); in addition there is an 'eastern' zone representing the edge of the Modum complex: these zones were probably inherited from the early regional structure.

THE MODUM COMPLEX

The Modum complex, the centre of which was surveyed by Jøsang (1966), is somewhat of an enigma in the Kongsberg Series. It contains quartz–plagioclase–mica gneisses and schists (± cordierite and almandine), sillimanite-rich rocks (± quartz–sillimanite 'nodules') and thick, pure quartzites: it also has later scapolitised gabbros, orthoamphibole–cordierite rocks, large pegmatites and albites. It has been likened to the Bamble Series of the Skagerrak coast (Bugge 1926, Jøsang 1966) and it was recently noted (Starmer 1980) that all these lithologies are typical of the Bamble Series and contrast with those of the surrounding Kongsberg Series. Isolated sillimanite-bearing gneisses were found by Hofseth (1942) in the Kongsberg Series west of Hønefoss and they also occur at Eiker (6 km WSW of Hokksund). A few, thin quartzitic layers occur east of Sokna. However, these are all isolated developments and differ from the constant association of thick quartzites with sillimanite-rich rocks, which is a feature of both the Modum complex and the Bamble Series.

The development of the Modum complex correlates with the lithological changes between major units in the early regional structure. It seems to represent an elongate domal area, modified by transposition and brought up by a combinaton of folding and later faulting. Its western margin (Figs. 1, 2 & 3) is defined by a late fault from Krøderen to Simoa, and further south (to Hokksund) by an earlier mylonite zone along which an upthrust of the Modum complex has occurred (Starmer 1980). Around Modum, Jøsang (1966) identified two southward-closing, major folds (which appear to have N to NNW axial planes, consistent with the regional pattern). Both are depicted on Fig. 1: one closure is in quartzite, north of Modum and the other is a 'syncline' at the southern end of the large granitic mass. Elsewhere and particularly further south (ie. west of Modum), no definite major folds were recognised, possibly due to the transposition effects observed elsewhere in the early regional structures.

In the present study, the detailed survey of the western part of the Kongsberg Series (Figs. 2–5) was extended eastwards to cover part of the Modum complex. The western margin of this complex consists of quartz–plagioclase–biotite gneisses with hornblende and almandine and with layers of biotite/phlogopite schist and thin quartzites: a little further east sillimanite gneisses, sillimanite granites and thicker quartzites occur. Almandine is common in all rocks. A few thin protomylonites and mylonites are developed. In the centre of the complex is the Brennåsen granite gneiss, which is largely homogeneous, but has marginal granitised patches of quartz–plagioclase–biotite gneisses, augen gneisses, sillimanitic and 'nodular' rocks and cataclastites. Thin granitic and granitised layers are developed around the main mass and these extend northwards (to the east of Krøderen village). East of the Brennåsen mass, sillimanite gneisses and schists (commonly reaching 2 mm grain size) frequently contain quartz–sillimanite lensoids (5–15 cm in length and 5 mm in width) often intensively retrogressed to muscovite. These lithologies are identical to the 'nodular rocks' in the Bamble Series of the Skagerrak coast.

The western part of the Kongsberg Series

VARIABLE QUARTZ–PLAGIOCASE–BIOTITE GNEISSES

These gneisses show great modal variations, with hornblende and almandine becoming more abundant eastwards. Textures are granoblastic and lepidoblastic to cataclastic, with grain sizes from 5 mm to $<$ 0.2 mm, respectively. (Rusty 'fahlbånds', common further south and in the Tyrifjorden–Soknadal tract to the east, are conspicuously absent in this area.) Isolated thin bands of protomylonite and mylonite occur throughout the area, becoming more common westwards towards the ultramylonite zone, where several major bands have been distinguished (Fig. 2). Layers of amphibolite occur: some concordant, coarse-grained bodies represent basic layers or early intrusives within the original supracrustals, but thin, finer-grained amphibolites form numerous concordant and discordant bodies and are related to the younger 'Vinor' intrusions.

The north-south striking gneisses undergo gradational, but significant changes eastwards across their strike: on a regional scale, this partly reflects the early regional structure and partly reflects the presence of a series of thrust slices, passing upwards to the east. Between Haugesjø and Krøderen (Fig. 2) the changes are sufficiently marked to separate the gneisses into a 'western', a 'central' and an 'eastern' (Modum complex) zone.

The 'western zone' consists of fine- to medium-grained quartz–plagioclase–biotite protomylonites and gneisses. Some layers are biotite-poor or biotite-free and a few contain muscovite or hornblende and/or almandine. One major band of coarser protomylonite and gneiss in the southwest (Fg. 2) contains 1 cm-size plagioclase porphyroclasts and reflects early banding, being cut discordantly by cataclased layers.

The 'central zone' is distinguished by the alternation (on a scale of a few cm) or m) of 'western zone' type gneisses and protomylonites interlayered with coarser variants containing 1 cm-size plagioclase porphyroclasts and augen. Biotite, hornblende and almandine are more abundant than in the western zone. The coarser layers become less common northwards towards Krøderen (Fig. 2) and very sporadic further north (Fig. 4).

The 'eastern zone' of gneisses (Fig. 2) belongs to the Modum complex, considered above. Although its western boundary is partly defined by a late fault, the change to this eastern zone is marked by developments of biotite schists and thin quartzites in the quartz–plagioclase–biotite gneisses.

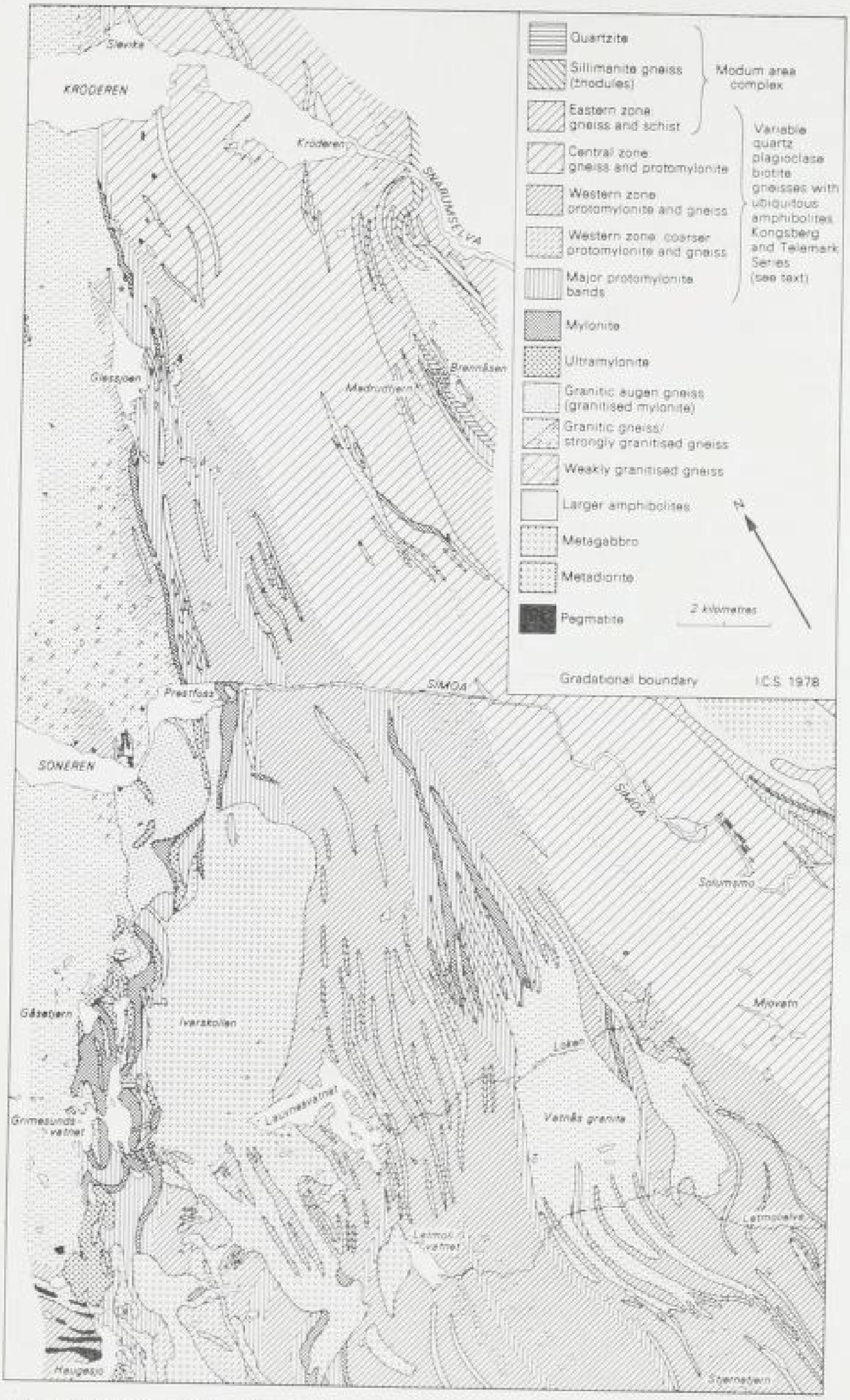

Fig 2. Lithological map of the area from Haugesjø to Krøderen.

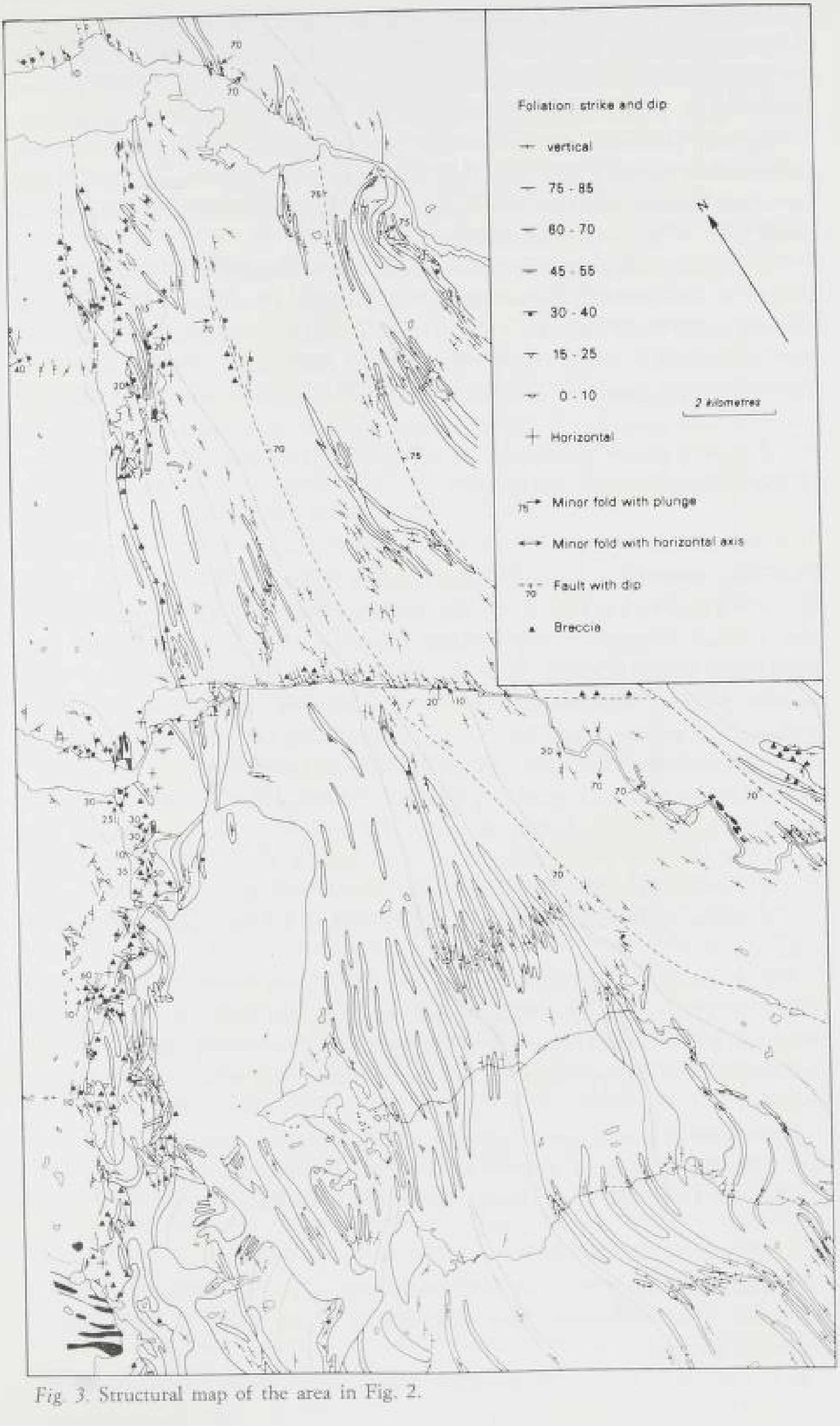

Fig. 3. Structural map of the area in Fig. 2.

North-eastwards from Krøderen to Sokna (Fig. 4), most gneisses resemble those of the central zone, but the coarser-grained types with plagioclase augen are less common (see above). East and northeast of Sokna (Fig. 4), the gneisses contain more hornblende and almandine and thin amphibolites are commoner: further east (between Vælsvatnet and Begna) variable gneisses contain some biotite schist layers, a few very thin quartzites and some amphibolites. These are subtle changes probably inherited from lithological differences between the major units of the early regional structure.

Throughout the area, almandines grew across cataclastic fabrics and were broken by later faulting and brecciation. Some early almandines (notably in the western zone) were broken by the cataclasis. Shadowy microclines (associated with granitisation effects from the Telemark, Brennåsen, Vatnås and Vælsvatnet granites) overgrew cataclastic fabrics and, together with later clinozoisite–muscovite growths ($\pm$ biotite, pistacite), were granulated by faulting and brecciation. Extreme retrogressions produced quartz–plagioclase–biotite–muscovite–epidote gneisses and schists.

THE 'VATNÅS GRANITE'

This body of pink-red granitic gneiss (usually called the 'Vatnås granite') lies between 6 and 14 km east of the ultramylonite zone (Fig. 2). It was an intrusive granite, elongated in the regional structure with thick, concordant apophyses and internal fabrics. It is a medum-grained granitic gneiss with some massive patches. Subequal proportions of microcline, quartz and plagioclase, with some hornblende and biotite, are accompanied by occasional almandine. Late muscovite and clinozoisite are often associated with biotite.

The granite cuts, and variably granitises, quartz–plagioclase–biotite gneisses and a north-south belt of protomylonites and mylonites. Thin, concordant and discordant sheets of amphibolite occur in the granite and its country rocks and all these lithologies may have later shear fabrics and mortar textures cut by granitic veins, aplites and pegmatites (which extend 2.5 km west of the granite margin).

The intrusion of the Vatnås granite was dated at $\sim$ 1370 m.y. by Jacobsen & Heier (1978). It cuts a mylonitised zone, but has undergone subsequent cataclasis, and was then reworked to form granite veins, aplites and pegmatites. It is therefore of critical importance in the synthesis of a sequence of geological events.

Thin veins of garnetiferous granitic gneiss occur just southwest of Simoa, near Solumsmo. They lie about 4 km east of the northern tip of the Vatnås granite, but are of the same relative age as the main body of granite.

THE 'TELEMARK GRANITE'

The 'Telemark granite' (or 'Telemark gneiss–granite') forms a large body in the south, but thins northwards from Krøderen to Sokna, where it disappears in granitised gneisses.

It is a medium- to coarse-grained, red-pink granitic gneiss containing microcline, oligoclase, quartz and biotite with sporadic hornblende, muscovite and almandine. Despite some variations from granitic to granodioritic, monzonitic and adamellitic compositions, this large body is reasonably homogeneous over wide areas: it seems to be of igneous origin, causing extensive granitisation. It transgressed and granitised the ultramylonite zone and the early mylonite band, north of Prestfoss; shadowy microcline porphyroblasts and augen (reaching 1 cm and rarely 3 cm size) formed in mylonites and ultramylonites, with more intensive effects producing granitic augen gneisses, south of Prestfoss. Some early amphibolites were apparently metasomatised during emplacement of the granite. North of Prestfoss, the granite included some of the early mylonite band (e.g. north of Langevatnet) but subsequent severe cataclasis affected it. The development of foliation and the growth of garnets reflect the Sveconorwegian regeneration which also reworked the granite producing veins and pegmatites.

On the north shore of Soneren, variably granitised plagioclase–quartz–biotite–hornblende gneisses have very shallow and variable dips and probably represent the roof levels of the Telemark granite body.

Ampibolite sheets cut the granitised rocks and a few cut the Telemark granite. Microcline porphyroblastesis in the amphibolites is related to later granitic pegmatites, aplites and thin granitic veins, representing a regeneration of the Telemark granite and cutting all lithologies (and the concentric folds). Larger, discrete pegmatite bodies (e.g. on the south shore of Soneren) may carry almandine, magnetite, zircon, orthite and sphene, all of which occur in the granite itself.

Friction breccia effects were intensive near the margin of the Telemark granite and frequently disrupted the pegmatites.

THE VINOR METAGABBROS, METADIORITES AND AMPHIBOLITES

This intrusive phase consisted of a series of injections, now forming some large bodies comprised of coronite, metagabbro, amphibolite and minor metadiorite. A separate series of later amphibolite dykes cut the larger bodies and their country rocks over the whole area. All these intrusives cut the ultramylonite zone and the mylonite band (north of Prestfoss), but may also show later shearing. Microcline and plagioclase porphyroblasts developed adjacent to pegmatites associated with the Telemark, Vatnås, Brennåsen, Vælsvatnet and Ådal granites. The late amphibolite dykes cut all these bodies, except the Ådal granite.

A number of large gabbro bodies are shown on the maps (Figs. 2–5). Throughout the area, elongate, subconcordant sheets of amphibolite and metagabbro have the same age relationships and are cut by the late amphibolite dykes. North of Simoa are a number of thick bodies of coarse, segregated amphibolite rich in garnet. They occur in Krøderen village, in Sokna, southwest of Rådalen, south of Nedre Vælsvatnet and in numerous sheets east and north of Vælsvatnet. They are cut by the amphibolite dykes and may represent earlier intrusions than the large metagabbro–coronite masses.

South of Prestfoss, in one large outcrop at its northwestern corner, the Ivarskollen gabbro overlies mylonite, with a contact dipping 30°E. Although this western margin is complex, the body may have been partly lopolithic, producing the extensive surface outcrop. On its eastern side (east of Lauvnesvatnet) the main body passes into metagabbro interlayered with gneisses on all scales. Southwards, the body develops an irregular outcrop representing the roof of the intrusion: some of the gneiss, protomylonite and mylonite southwest of Lauvsnesvatnet may be displaced, rafted material.

West of Prestfoss, on the north shore of Soneren (Fig. 2) a small metagabbro–amphibolite body cuts the Telemark granite and granitised gneiss. It was clearly emplaced after the Telemark granite, but is itself cut by amphibolite dykes and thick granitic pegmatites, the latter producing porphyroblasts of plagioclase (up to 1 cm in size) and some of microcline.

Small patches of metadiorite are massive or foliate. They occur in the metagabbros in a number of places (e.g. east of Haugesjø, along the west of the Ivarskollen body, at Vælsvatnet and east to Begna). Rarely they contain xenoliths of metagabbro, in which they have caused plagioclase porphyroblastesis. More commonly, foliate varieties contain amphibolite lenses (20–100 cm long) which are orientated parallel or at a small angle ($< 25°$) to the foliation. Plagioclase porphyroblastesis has converted some lenses to ghost relics. Often these rocks are also cut by the late amphibolite dykes. Both the host rock and the lenses may be similarly garnet-rich or garnet-free and occasionally the almandine is developed only as a rim on the lenses. This suggests garnet grade metamorphism after their inclusion. In a few cases, small dioritic patches (not shown on Fig. 2) within the metagabbros resulted from contamination by 'mobilised gneisses', which are more extensively developed south of the present area.

The late amphibolite dykes are usually 3–100 cm wide, but rarely reach several metres. Some are massive, but commonly they are foliated parallel to their margins and contain some biotite and more rarely garnet.

Dykes of several generations are present and in places they cut one another. Their orientations were partly random and partly controlled by the structure of the gneisses. In many cases they have caused the growth of poikiloblastic hornblendes in cataclased rocks (including the mylonites and ultramylonites). Boudinage of some bodies occurred during the concentric folding. Late fabrics of biotite, clinozoisite and pistacite are often strongly developed.

THE ÅDAL (FLÅ) GRANITE

In the north of the area (Fig. 4), the post-kinematic Ådal 'granite' (a quartz monzonite) was emplaced after the intrusion of the late amphibolite dykes and contains xenoliths of them. Granitic (and pegmatitic) injections, from the Ådal granite, cut rocks as far south as the Vælsvatnet metagabbro (Fig. 4): associated microcline porphyroblastesis in many places post-dated the development of clinozoisite. The granite intruded after the concentric folding and modified surrounding structures.

The western margin of the Kongsberg Series

From Kongsberg to Flesberg the margin of the Kongsberg Series is an early mylonite zone, dipping to the east, with the 'friction breccia' (due to late faulting) adjacent to it (Starmer 1977, 1979). From Flesberg, the mylonite zone continues north to Haugesjø (Fig. 1) with a layer dip decreasing from around 60° to ca. 30°E and becoming increasingly deformed by concentric folding. The thinning may be ascribed either to tectonic or to lithological controls. At Haugesjø, a complex basin structure and a break in the mylonite zone seem largely responsible for a major bend in the Kongsberg Series' margin, which then trends northeast into the present area.

From Haugesjø to Prestfoss (Figs. 1–3) the ultramylonite is intensely deformed by concentric folds, but continues northeast, having been sandwiched prior to the folding between a coarse 'Telemark granite' to the west and a large gabbro to the east. At Prestfoss, it is deformed into another major basin structure. Further north, the margin changes character, with a narrower band of mylonite and protomylonite, diminishing northwards to Sokna and branching south of the Ådal granite (Figs. 1 & 4). Later faults and breccias follow the entire margin and some occur north of the Ådal and Hedal granites.

Hageskov (1979, 1980) suggested that the 'real brecciated part' of the shear zone disappeared around the Sperillen (Ådal) granite, but that the 'heavily sheared and blastomylonitic rocks of the shear zone' continued north to Bagn. From Kongsberg to Sokna, 'a strongly deformed linear belt' followed northwards along the shear zone: just west of Sokna, Hageskov suggested both were deformed by a rather tight, late fold and changed orientation from northeast to northwest, subsequently turning north (approximately along the line of the fault shown on Fig. 1) to be cut by the Flå (Hedal) granite and reappearing on its northern side at Bagn. The folded shear zone and accompanying linear belt striking from NW to NNW between Sokna and the Ådal granite are not consistent with structural trends observed by the present author (Figs. 1, 4 & 5) or by Smithson (1963).

The present study suggests that the main shear zone (the 'mylonite band') dissipated northeastwards towards Sokna, from where it continued with the same general trend, splitting along several lines and being broken by later folding. The 'heavily sheared and blastomylonitic rocks' found by Hageskov to the northwest of Sokna are not considered to represent the main shear zone, but may reflect the branching on several movement planes and may be partially related to later faulting.

The cataclased zone at Bagn (about 70 km northnorthwest of Sokna) continues for 8–10 km northeastwards through Bruflat. This zone (shown on Fig. 1) was described by Strand (1954) and Smithson (1963) and consists of sheared granitic augen gneisses and mylonites with a N to NW dip and a lineation down-dip: its orientation is related to that of the Caledonian belt which it underlies. The zone forms a boundary between two major divisions in the Precambrian basement, with quartz–dioritic gneisses to the north and granodioritic gneisses to the south.

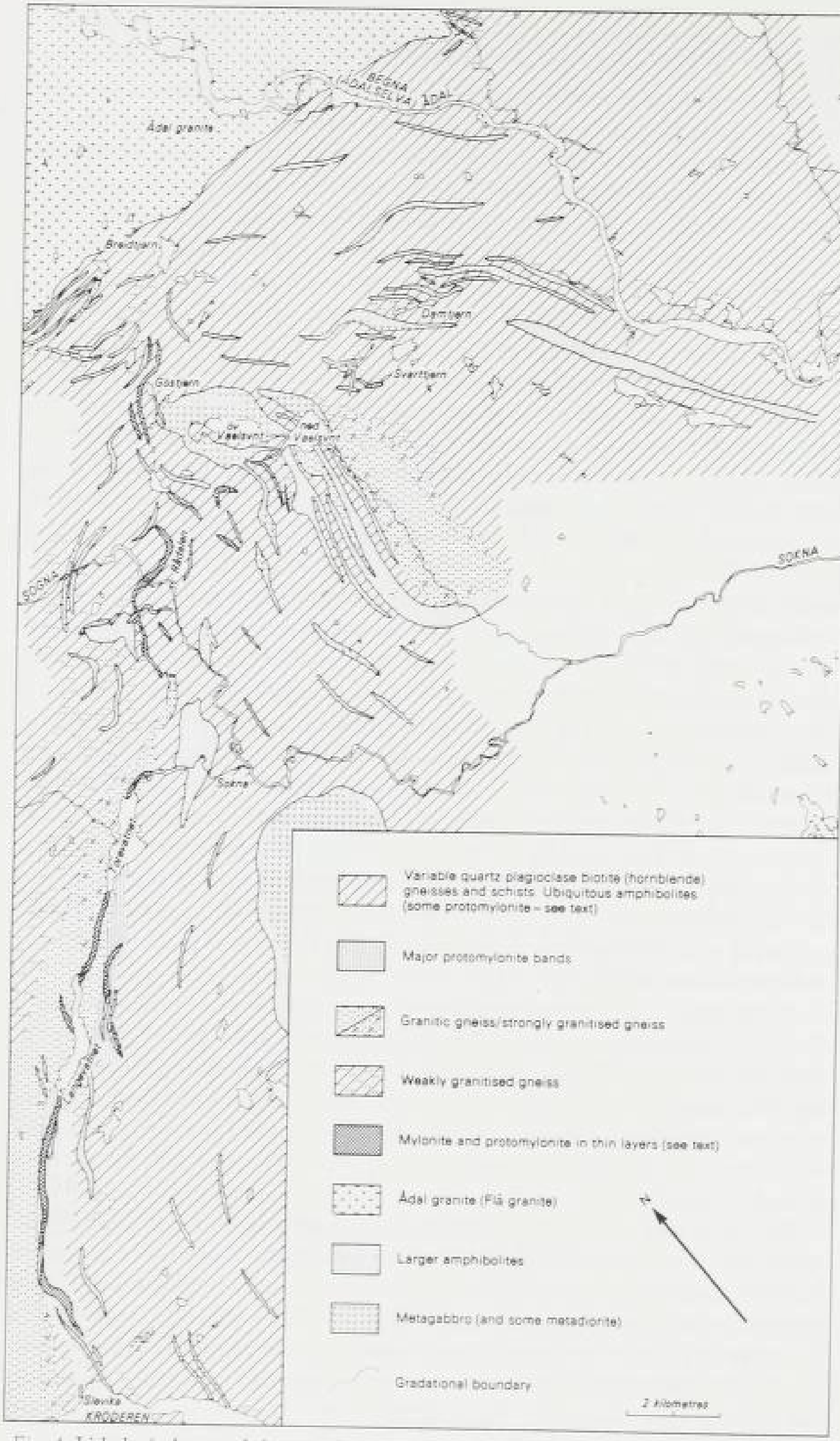

Fig. 4. Lithological map of the area from Krøderen to Ådal. (Note that the orientation and scale are not identical to those of Figs. 2 & 3.)

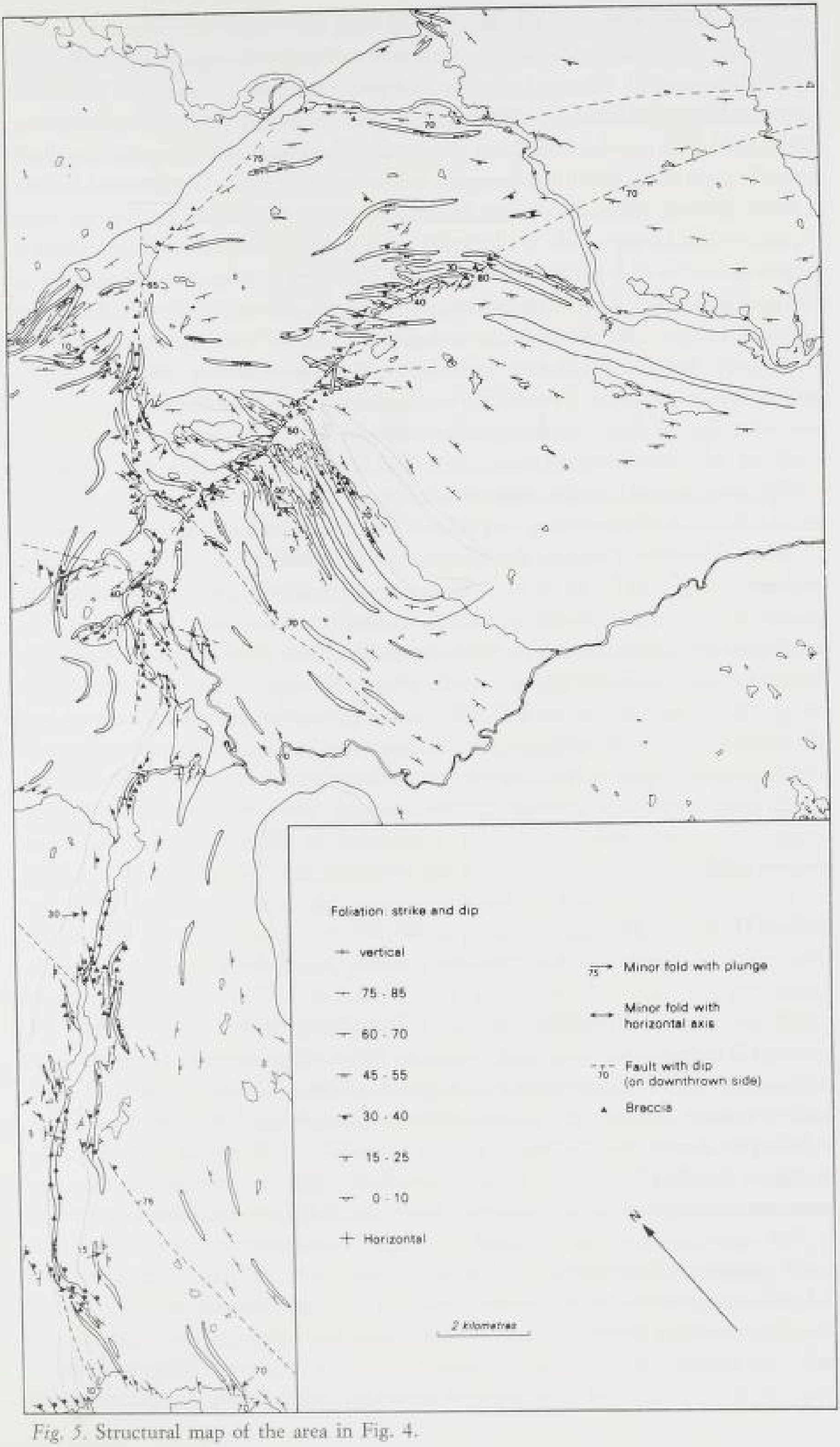

Fig. 5. Structural map of the area in Fig. 4.

THE ULTRAMYLONITE ZONE SOUTH OF PRESTFOSS

This zone, discussed in detail from the area immediately to the south (Starmer 1979), consists of ultramylonite (< 0.1 mm grain size), mylonite and some protomylonite, which were partially granitised to augen gneisses by the underlying Telemark granite. The zone was sandwiched between the granite and the large Ivarskollen gabbro (to the east) before being complexly deformed by concentric folding. Complex major basin structures developed in the north at Prestfoss and in the south at Haugesjø. At Prestfoss, the main basin formed in augen gneisses and granitised mylonites, but just to the east the structural pattern is simpler with mylonites and thin metagabbros concentrically folded together in separate folds on axes plunging moderately southeast and northeast.

East of the ultramylonite zone, there are numerous thin bands of protomylonite and mylonite. West of Letmolivatnet, protomylonite contains lensed-out amphibolite sheets and may reflect late, strike-slip movements, the importance of which will be discussed later. The Vatnås granite cuts thin mylonites within protomylonite (generalised on Fig. 2): these are often granitised and recrystallised and sometimes overgrown by coarse muscovite and clinozoisite.

Where the effects of late deformations can be reliably removed in the ultramylonite zone (and where there is no steepening against the gabbro), porphyroclasts record NW–SE stretching lineations in an early foliate layering, with minimal flattening perpendicular to it. The shear planes dipped moderately southeast (at around 40–60°) with a down-dip sense of movement. This is compatible with the present NE–SW orientation of the ultramylonite zone and the general westward upthrust found in areas to the south. The intense granulation occurred before microcline porphyroblastesis, but sometimes the K-feldspars were later rolled (by dip-slip movements). Subsequent growths of clinozoisite, muscovite and biotite were granulated by the friction breccia movements, with sporadic later overgrowths of calcite.

THE MYLONITE BAND NORTH OF PRESTFOSS

The western margin of the Kongsberg Series, north from Prestfoss to Glessjøen (Fig. 2), is a thin mylonite band (generally < 150 m and sometimes < 50 m wide) locally containing thin ultramylonite layers. North from Glessjøen, it diminishes and the band shown on Fig. 4 often consists of thin mylonite layers (< 5 m thick) alternating with protomylonite. North of Sokna, it splits into a number of thinner, more weakly cataclased bands broken by folding. Although close to the Telemark granite margin from Prestfoss to Sokna, the mylonite band is commonly bounded on both sides by similar gneisses and protomylonites (traditionally separated into the Telemark or Kongsberg Series).

The mylonite band was originally formed before emplacement of the Telemark granite and is incorporated as large enclaves in the latter (e.g. north of Langevatnet). Subsequent, severe cataclasis occurred before the late brittle faulting, crushing microcline porphyroblasts in the mylonites and shearing the adjacent granite. All the later movements were concentrated along the granite margin, the mylonites dissipating and branching where the granite terminated north of Sokna. Microcline porphyroblastesis in the mylonite was usually associated with late pegmatites, aplites and thin granitic veins. In a few places (e.g. around Glessjøen), granitisation (presumably from the adjacent Telemark granite) occurred before intrusion of amphibolites which were subsequently sheared and cut by pegmatites. The mylonite band was intruded by the gabbros and the amphibolite dykes, deformed by concentric folding, injected by pegmatites and aplites, overgrown by clinozoisite and broken by the friction breccia movements.

The mylonite band was deformed by minor concentric folds and a few larger, open flexures which, north of Sokna, become tighter, giving major folds (which disrupted the mylonite band). From Sokna south to Krøderen, the mylonite curves, partially following the major structure, and generally dips 30–50° SE or ESE; further south, from Krøderen to Prestfoss, it dips 50–80° ESE and the lack of folding facilitates an analysis of movements.

Cataclasis in the mylonite and adjacent protomylonite occurred on these dipping planes, with early dip-slip movements and subsequent, minor displacements which were either strike-slip or oblique, pitching 20–40°N. In some places, monoclinal microfolds (deforming the early cataclasis fabric and lineations and cut by pegmatites) were formed during the second movement and show that the eastern (Kongsberg Series) side moved south and in places obliquely upwards, with little compressive stress normal to the shear planes. Some intruded amphibolites show only the strike-slip or oblique-slip lineation (with some microfolds) suggesting that they intruded after the earlier movements. Just north of Slevika, thin, subconcordant amphibolites intruded mylonite, but their apophyses were streaked out by strike-slip displacements during injection. Amphibolites thus intruded before, during, and after later movements within the mylonite.

East of the mylonite band, thin cataclased bands resulted from various movements. In the 'central zone' gneisses, southwest of Medrudtjern (Figs. 2 & 3), plagioclase porphyroclasts record strike-slip movements and nearby lineations suggest oblique displacements, pitching 40–60°S on N-S planes.

LATE FAULTING AND 'FRICTION BRECCIA' MOVEMENTS

The friction breccia, traditionally taken as the boundary to the Kongsberg Series, is represented by a diffuse faulting and brecciation of the earlier ultramylonite and its adjacent rocks south of Prestfoss. Northwards, from Prestfoss to Sokna, the breccia largely followed the mylonite band, but north of Sokna it split along several lines, partly following the mylonites (which had branched here) but cutting their folded structures. Some very thin mylonites were associated with this late, brittle faulting.

The brecciation affected all rocks (including the pegmatites): minor faults cut the Ådal granite and there was some shearing around its margins. The displacements produced granulation and mortar textures, breaking overgrowths of microcline and clinozoisite. A veining of quartz, calcite, chlorite and epidote is also sometimes disrupted by the late movements.

The friction breccia resulted from a series of movements, with an overall normal displacement and downthrow of the southeast (Kongsberg Series) side. It was part of a regional system of faults (showing a series of movements) and is linked to the perpendicular Simoa fault, trending southeast from Prestfoss and downthrowing the Kongsberg Series to the north. The Simoa fault continues southeastwards in a breccia north of Solumsmo (Figs. 2 & 3), before being cut out by a NNW–SSE fault which here forms the western margin of the Modum area complex: small drag folds show that at least one movement involved an upthrow of the eastern (Modum) side. No westward continuation of the Simoa fault was found in the Telemark granite west of Prestfoss, and its maximum movement was in the sector east of the friction breccia with which it was obviously linked. However, there may have been parallel faults westwards in lake Soneren. Along the Simoa fault, granulation and mylonitic fabrics were overgrown by clinozoisite, which was cracked by later movements, indicating a series of displacements similar to those on the friction breccia.

North of Sokna, several major faults are distinguished (Fig. 5) and intervening minor faults form a mosaic. The main breccia trends northeast from Sokna across the Sogna river into Rådalen, where the southern side is downthrown. It then splits, with a number of branches trending from due north to due east. In Begna, just south of the Ådal granite, a brecciated fault dips steeply southwest and has drag folds showing a late strike-slip, with the southwest side displaced southwards. Many of the brecciated minor faults are either parallel to the major friction breccia lines or are markedly transverse, sometimes subparallel to the Begna fault and showing the same late strike-slip.

Folding and general structure of the western Kongsberg Series

The Kongsberg Series structurally overlies the Telemark Series along a cataclased junction. In the Kongsberg Series, the earliest recognisable foliation is a penetrative fabric parallel to transposed lithobanding: rare intrafolial isoclines are preserved. The foliation was overprinted (particularly in the extreme west) by almost coplanar cataclastic fabrics and the structure was later complicated by concentric folding and accompanying deformation around large gabbros.

In the southern part of the area (Figs. 2 & 3), the north-south structure and discontinuous lithobanding of the western Kongsberg Series continue as far north as Krøderen. East of the ultramylonite zone (and the Ivarskollen gabbro), the foliation and banding generally dip very steeply east to vertical. The dips change to become steeply west to vertical across the Vatnås granite and to the east of it. The change occurs just west of the Vatnås granite and can be traced further south (to the south of the present area): this seems to represent a major N-S synform developed prior to the formation of the ultramylonite zone and the intrusion of the Vatnås granite. North of the Simoa fault to Krøderen, the general structure dips 55–75°E.

Further north, the major structure turns northwest from Krøderen to Sokna, with a moderate dip southeast, probably partly related to deformation around a large metagabbro. North of Sokna, a complex folded pattern has developed towards the Ådal granite.

Concentric, buckle folds and flexures developed after intrusion of the late amphibolite dykes, but before the pegmatite activity. Two sets of folds interfered on all scales, giving domes and basins in the Telemark Series (including the previously foliated Telemark granite), in the mylonite zones and in the Kongsberg Series where the folds become less common eastwards. Many were small, open flexures (or domes and basins) on foliation planes and did not significantly alter the layer dip. Others were minor flexures or better defined concentric folds with wavelengths from 1 m to 10 m and much smaller amplitudes. Larger flexures and folds affected the major structures, notably at Haugesjø and Prestfoss, forming basins in the ultramylonite, and north of Sokna, breaking the mylonite band and producing disharmonic folds with considerable transposition. Axial plunges vary and were largely controlled by the previous structure, but many are low to moderate to the northeast and southeast (becoming N-S and E-W in places). Axial planes are normally subvertical, but in places north of Krøderen, are overturned to the east and in rare cases are subhorizontal.

Synthesis and discussion

Away from its western margin, where a later, N-S cataclastic banding was variably superimposed, the Kongsberg Series retains remnants of an 'early regional structure' with major domes and basins developed during upper amphibolite facies metamorphism. Even 5–10 km east of the ultramylonite zone (at the western margin) there seems to be a relict, major synform on the west side of the Vatnås granite.

The early regional structure may have contributed towards a number of features (e.g. the distribution of fahlbands in the supracrustal gneisses). The bend in the ultramylonite at Haugesjø is now largely controlled by a basin structure (Starmer 1979), but further north the northeastward trending ultramylonite was sandwiched between the Telemark granite and the large gabbros before the concentric fold phase, which produced the basin. Some early curvature of the ultramylonite zone may therefore have existed and could have developed in quartz-rich rocks deformed around the early regional structures.

It has already been noted that the rocks of the Modum complex differ from those in the surrounding Kongsberg Series and are remarkably similar to those in the Bamble Series, and that the location of this complex could be explained by the early regional structure. Although the Bamble and Kongsberg Series contain rather different lithologies, they underwent the same sequence of major events (Starmer 1977): they may have been deformed together in the Svecofennian orogeny, the Modum complex representing Bamble Series rocks infolded into the Kongsberg Series. There has also been a relative uplift of the Modum complex along its western margin, the movement producing an early mylonite zone with an adjacent, later fault. The constant association of thick, pure quartzites and sillimanite-rich rocks in early domes and basins, with transposition and isolation of some structures, is seen in Svecofennian folding of both the Bamble Series (Starmer 1978) and the Modum complex. Later events in both the Bamble and the Modum (before and during the Sveconorwegian Regeneration) included scapolitisation of newly-intruded gabbros and the development of orthoamphibole–cordierite rocks, large pegmatites and albitites, indicating possible retention of contiguity at that time.

The Kongsberg Series was thrust westwards, its earlier dome and basin structure becoming partially modified to a north-south banding in its western parts. The frontal thrust and original western margin was the ultramylonite zone, preserved only in the widest part of the Kongsberg Series and cut out north of Prestfoss by the 'mylonite band'. Brecciation of this mylonite band (producing the 'friction breccia') and movement on the Simoa fault downthrew the Kongsberg Series north of Simoa, leading to the exposure of higher structural levels. This partly cancelled the original displacement on the mylonite band, especially further north where the movement had been less. This hingeing effect, probably influenced by the early regional structure, may have affected only the western margin, since there were numerous movement planes to the east. The hingeing and the late faulting, coupled with a decreased dip and retention of some of the early regional structure, led to exposure of similar rocks on either side of the friction breccia: there is no significant difference between supposed 'Telemark' and 'Kongsberg Series' rocks on either side of this breccia zone.

The ultramylonite zone was cut out at Prestfoss by a combination of the steeper, brecciated 'mylonite band' and the Simoa fault. It could have terminated here originally due to lithological changes related to the early regional structure (e.g. the disappearance of quartz-rich rock necessary for its development). The formation of the later basin structure in the ultramylonite at Prestfoss was partly controlled by its position at the northern end of the Ivarskollen gabbro.

The mylonite band north of Prestfoss developed after the ultramylonite zone, but synchronously with other cataclased belts further south, from Prestfoss to Haugesjø. These include mylonites along the eastern side of the ultramylonite and augen gneiss, late shears in the ultramylonite, and mylonite–protomylonite zones lying southwest of Lauvnesvatnet. Some of the mylonite band's later movements were synchronous with the shearing of metagabbro layers east of Lauvnesvatnet and the strike-slip displacements correlated with the lensing-out of amphibolite in protomylonite, west of Letmolivatnet.

Radiometric work places some contraints on the age of major events. The Rb–Sr data of Jacobsen & Heier (1978) recorded two major metamorphisms in the southern Kongsberg Series at about 1600–1500 m.y. and 1200–1100 m.y. B.P. ($\lambda = 1.39 \times 10^{-11} \cdot yr^{-1}$). The 'Telemark granite' of the present area has a similar lithology to the Helgevatnet granite, intruded at around 1200 m.y., and reconnaissance of the latter reveals a similar relative age (in terms of cataclasis, amphibolite dyke intrusions, etc.). The radiometric data of Jacobsen

& Heier can be combined with the sequence of events in the present area to produce the following history:

1) Supracrustals (now variable quartz–plagioclase–biotite gneisses and some amphibolites) were deformed into major dome and basin structures during Svecofennian upper amphibolite facies metamorphism (1600–1500 m.y.).
2) Westward upthrusting of the Kongsberg Series produced the ultramylonite zone (south of Prestfoss) during middle to upper amphibolite facies metamorphism.
3) Initial formation of the 'mylonite band' (north of Prestfoss) during amphibolite facies metamorphism.
4) Vatnås granite intruded (cutting a cataclased belt) (~ 1370 m.y.).
5) 'Telemark granite' intruded (~ 1200 m.y.).
6) Renewed cataclasis (particularly around the 'mylonite band' north of Prestfoss).
7) Vinor gabbros intruded (one body cutting the 'Telemark granite'). (~ 1200 m.y.).
8) Upper amphibolite facies metamorphism.
9) Intrusion of Vinor dykes (now amphibolites). (Probably before 1070 m.y.).
10) Weaker cataclasis (including strike-slip movements).
11) Concentric folding (in places forming domes and basins) on all scales.
12) Formation of granitic veins, aplites and pegmatites by reworking of the Telemark, Vatnås, Brennåsen and Vælsvatnet granites.
13) Epidote–amphibolite facies metamorphism giving overprints of epidote and muscovite in all rocks.
14) Ådal granite intruded (~ 913 m.y.) (date of Killeen & Heier 1975).
15) Brittle faulting (initially at lower to middle greenschist facies) producing the friction breccia and the Simoa fault.

In this sequence of events, elements 8 to 13 inclusive constitute the Sveconorwegian Regeneration.

Periodic cataclasis occurred over an extended period of time. Some early movements took place before the intrusion of the Vatnås granite (~ 1370 m.y.) and the western ultramylonite zone formed before the Telemark granite was emplaced (~ 1200 m.y.). Subsequent severe cataclasis, particularly in the 'mylonite band' north of Prestfoss, affected the Telemark granite, and weaker, later shearing occurred during and after the intrusion of amphibolite dykes.

The earlier movements, prior to the emplacement of the Vatnås and Telemark granites, have been considered to represent a westward thrusting of the Kongsberg Series over the Telemark block. Southwards from the present area, the dip of the western mylonite zone steepened from around 60°E at Flesberg to some 70–80°E where it disappears beneath the Oslo Graben. (The latter orientation is taken from Starmer (1977) with removal of the subsequent southeastward tilting of the Oslo Graben.) The orientation of the western mylonite zone indicates that, at the levels exposed south of the present area, vertical displacements predominated over horizontal motions. Thrust zones commonly steepen in depth due to a re-orientation of the stress trajectories, and the lack of flattening perpendicular to the layering of the mylonites may suggest that (at the exposed levels) east-west compressive stresses were not the dominant forces. The movement, therefore, could also be considered as a net downsinking of the Telemark region, leading to anatexis and production of large volumes of Telemark granite.

Subsequent gabbro intrusions and dykes indicate a period of rifting which was aborted by the onset of the Sveconorwegian Regeneration.

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