The Kongsberg Series Margin and Its Major Bend in the Flesberg Area, Numedal, Buskerud

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This major boundary is shown to be defined not by the traditional 'Friction Breccia', but by a much earlier and more extensive mylonite zone. The mylonitisation was produced by a complex westward upthrust of the Kongsberg Series over the Telemark Series; both blocks had a common history thereafter. Spatial and chronological relationships between the upthrusting, an extensive series of gabbroic intrusions and an increased regional heat flow, suggest association with major crust – mantle processes. The only major bend in the Kongsberg Series margin occurs in this area and its location and development are explained.

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Introduction and general geology

The area lies some 20 km north of Kongsberg, around the villages of Flesberg, Lampeland and Lyngdal (Fig. 1) and is part of that described by A. Bugge (1937) in the memoir 'Flesberg og Eiker'. It is also included on the 1 : 250,000 map sheet 'Skien' (Dons & Jorde 1978). Bugge (1937, p. 111) considered that 'a great friction breccia 100–300 m wide, locally even wider, marks the boundary between the Telemark Formation and the Kongsberg Formation'. This 'rivningsbreccie' (friction-breccia) was described as a typical brittle-fracture, crushing the adjacent 'Kongsberg-granitt' which formed a continuous marginal strip to the Kongsberg Formation.

The present survey shows that the 'friction breccia' was a late, brittle fracturing, which was not of regional significance. The Kongsberg Series (to the east) and the Telemark Series (to the west) were separated by a much earlier, more major zone of mylonite (exceeding 1 km width) which was subsequently deformed and metamorphosed, with ubiquitous microcline porphyroblastesis. More intensive granitisation produced sporadic augen gneisses, probably equivalent to the 'Kongsberg-granitt (Øiegranitt)' of Bugge (1937). These augen gneisses, however, do not form a continuous marginal strip on the Kongsberg Series and were initially part of the mylonite zone. The term 'Kongsberg granite' has not been retained, since it has also been variously used, in areas to the south, for different bodies both east and west of Kongsberg. Moreover, in the present area, these granitic augen gneisses cannot be considered unequivocally as part of the Kongsberg Series.

Within the present area, some 10 km north of Flesberg (Fig. 1), the Kongsberg Series margin undergoes its only major bend from a N–S trend in the southern part to a NE–SW orientation further north. This bend (see key map

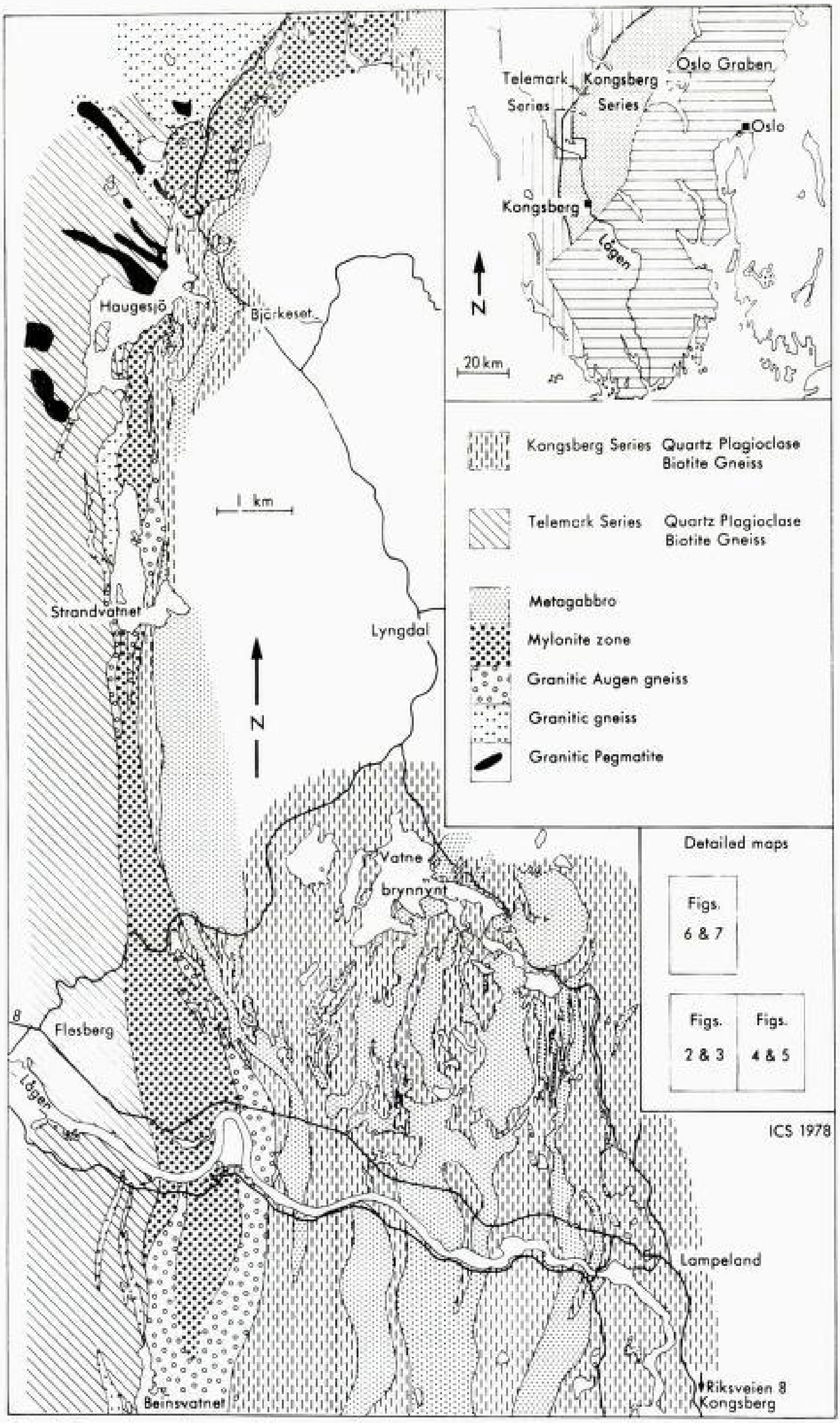

Fig. 1. Location and general features of the area.

of Fig. 1) is a gradual deflection of the boundary on larger scale maps (Figs. 1 & 6) and is produced by a tectonic break in the mylonite zone, which is deformed by a complex basin structure. Northeast of the present area, the boundary (of heavily granitised mylonite) continues for about 9 km with an essentially planar outcrop pattern, despite considerable internal deformation by minor structures (Starmer, in prep.).

The Kongsberg Series consists of supracrustal gneisses intruded by a series of basic bodies, the so-called 'Vinor' intrusions. In the Flesberg–Lampeland district, numerous gabbroic outcrops have the surrounding gneisses deformed around them and represent protrusions from the irregular roof of a larger mass. This is probably the northern end of the large 'Vinoren' body of C. Bugge (1917) and A. Bugge (1937). Metamorphism altered the gabbros and, enhanced by an increased heat flow around the large Vinoren body, caused some mobilisation of the supracrustal gneisses.

The mylonite zone cuts across this complex with a planar outcrop, although it has been deformed and even broken in the north, around Haugesjø. Late, brittle (friction-breccia) fracturing and associated hydrothermal veining were particularly concentrated around this mylonite zone.

The Telemark Series consists of cataclased supracrustal gneisses, granitic gneisses, amphibolitised intrusives and granitic pegmatites. These rocks have a much shallower dip than those of the Kongsberg Series, although lower angle dips also occur in the mylonite zone.

Thick drift occurs in the Lågen valley and has been shown on the maps Figs. 2 & 4) where extensive lack of exposure prevents accurate interpretation of bedrock. (The most probable interpretation is shown on a small-scale map of the general geology — Fig. 1).

Cataclastic rocks are of major importance and are decribed using the lithological nomenclature of Higgins (1971). In terms of the rationalised nomenclature of Zeck (1974) they show limited myloblastic recrystallisation (simultaneous with ruptural deformation) with dominant blastomylonitic recrystallisation (after mechanical degradation).

In the Kongsberg district (some 20 km south of the present area) reconnaissance radiometric work by O'Nions & Heier (1972) suggested that the rocks had undergone an early metamorphism around 1700 ± 100 m.y. and a second metamorphism around 1260 ± 40 m.y. ($\lambda = 1.39 \times 10^{-11} . yr^{-1}$). More recently, Rb–Sr isotope data presented by Jacobsen & Heier (1978) for rocks around Kongsberg, showed a maximum age for the crust of about 1600 m.y. ($\lambda = 1.39 \times 10^{-11} . yr^{-1}$). Two metamorphic episodes at about 1600–1500 m.y. and 1200–1100 m.y. were recognised, with a series of granitic rocks formed by anatexis of pre-existing crust. An intrusion age of 1200 m.y. was defined for the large gabbro at Vinoren. A sequence of geological events in the Kongsberg district, suggested by the present author (Starmer 1977) correlates completely with the radiometric data of Jacobsen & Heier (1978) and is compatible with the history of rocks in the Flesberg area. In particular, cataclasis at the

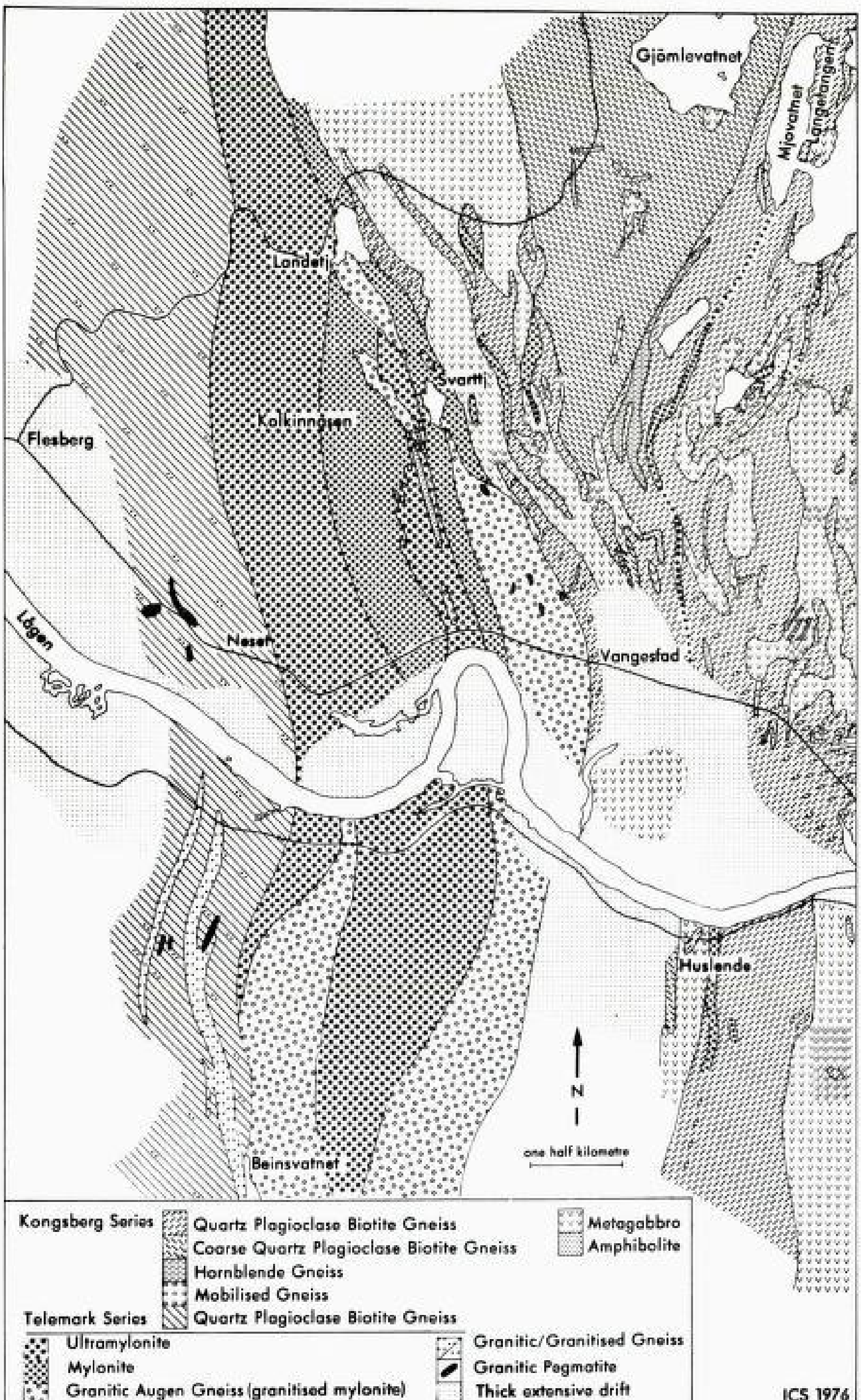

Fig. 2. Lithological map of the Flesberg area.

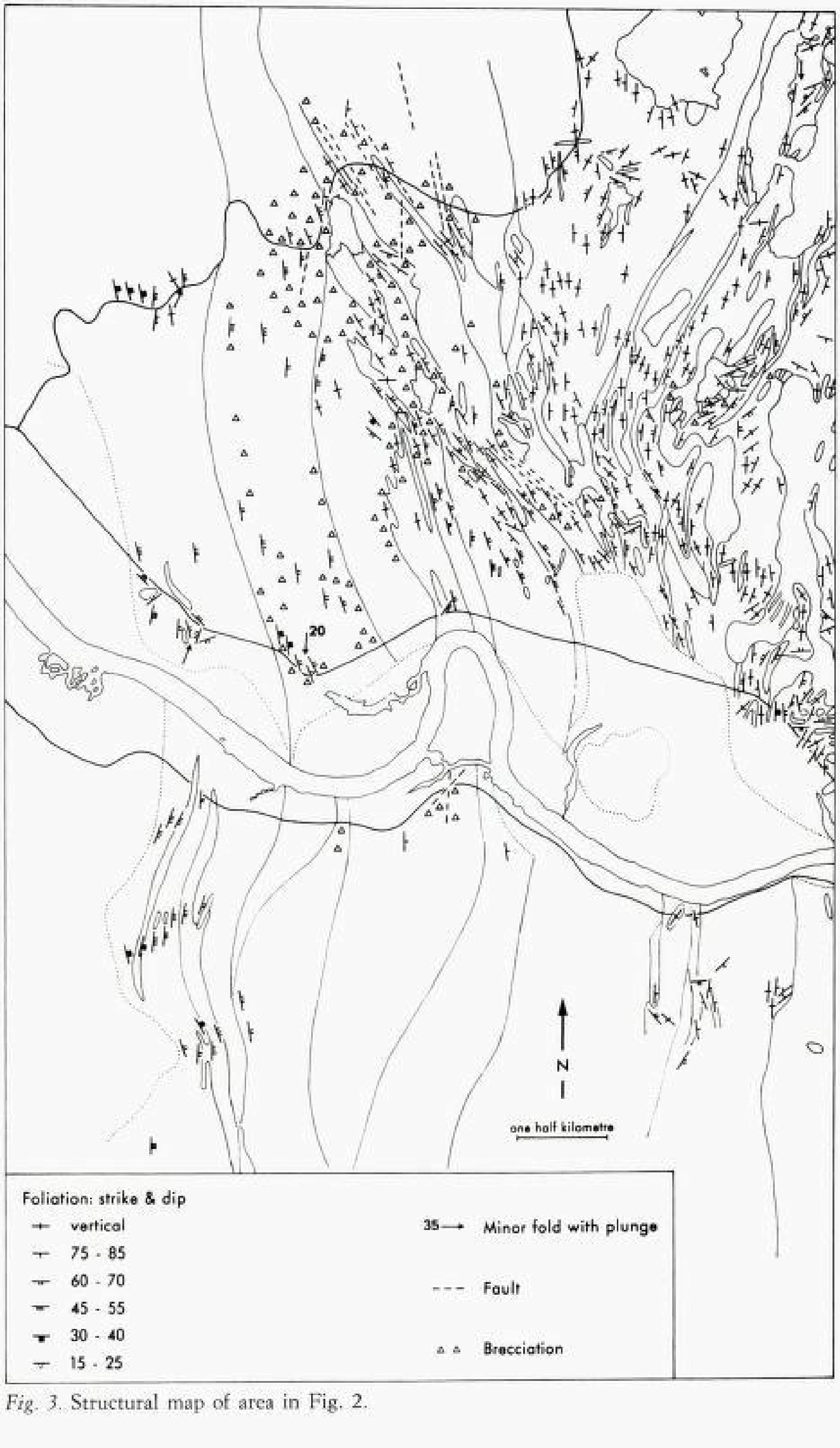

Fig. 3. Structural map of area in Fig. 2.

margin of the Kongsberg Series was thought to reflect uprise relative to the Telemark block, with besic Vinor intrusions emplaced during and after the closing stages of movement.

The mylonite zone

MYLONITE AND ULTRAMYLONITE

This zone (which really also includes the granitic augen gneisses, described subsequently) has the shallower dips, cross-folds and granitic pegmatites characteristic of the Telemark Series. In places, however, it contains less-altered enclaves of both Kongsberg and Telemark Series gneisses and it therefore seems inappropriate to assign it to either complex.

The main zone of ultramylonite (with sporadic mylonite and protomylonite) exceeds 1 km width near Flesberg and is gently flexured. It thins northwards towards Haugesjø, where it has a shallower dip, complicated by both major and minor folding: here, it is also more dominantly ultramylonitic, although less severe cataclastic effects are spread over a wider area than in the south.

The mylonite zone has a thoroughly transposive cataclastic fabric forming S-tectonites but, in many places, prominent stretching lineations or rolled porphyroclasts produce L–S tectonites. There were a number of movement phases and work is in progress to try to define these more precisely. The main mylonite–ultramylonite zone has fairly sharp boundaries, but on both sides the rocks show milder cataclasis, partly due to late movements taken-up by the surrounding gneisses after the competent mylonite zone had formed.

In the Kongsberg Series, protomylonites and sporadic mylonites are common over a distance of 1–2 km east of Flesberg (Figs 2–5). More isolated cataclasis occurs further east, particularly in a belt of mylonite just west of Lampeland where contemporaneity with the main zone is shown by a narrow ultramylonite cut by a thin Vinor amphibolite in Lyngdalselva. In the Haugesjø area (Figs. 6 & 7) the Kongsberg Series supracrustals are all mylogneiss and protomylonite, with occasional bands of mylonite. They become more severely cataclased westwards, towards the main mylonite zone.

The Telemark Series around Flesberg shows only weak cataclasis near the main zone, but further north in the Haugesjø area, the mapped rock are predominantly protomylonite and mylogneiss.

Everywhere within the ultramylonite and mylonite, isolated microclines (up to 1 cm size) grew across the lepidoblastic groundmasses of quartz (±plagioclase) which had been finely granulated (often to 0.1 or 0.05 mm size). Some quartz has recrystallised (to 0.2–0.5 mm size) in ribbons which rarely also contain microcline, suggesting contemporaneous crystallisation. Biotite (up to 1 mm) recrystallised after cataclasis, but is often ragged. Isolated plagioclase porphyroclasts (usually up to 3 mm, rarely 1 cm size) are variously sericitised and later intensely saussuritised after microcline growth. Occasionally the porphyroclasts are multi-crystal augen and may contain chloritised biotite. Some apparent augen are aggregates of fine, granulated groundmass (with or without a central plagioclase) surrounded by recrystallised streaks of coarser quartz and forming sites for microcline nucleation. Although there are some early garnet porphyroclasts, small (<5 mm) euhedral crystals have occasionally grown across the cataclastic fabrics.

The microclines are single or multi-crystal porphyroblasts (up to 1 cm or rarely 2 cm) forming isolated, rounded masses or irregular augen, with no preferred orientation. They are often replacive, shadowy perthite and antiperthite, nucleating on plagioclase porphyroclasts or forming poikiloblasts in the groundmass. In a few cases, weak cataclasis had caused minor granulation of the microclines.

In the mylonites and protomylonites, the effects were similar to those in the ultramylonites but finely granulated material developed only in certain bands, plagioclase porphyroclasts were more abundant and hornblendes recrystallised without retrogression.

The cataclased rocks all underwent late saussuritisation of plagioclase to clinozoisite. A late fabric of epidote associated with biotite and/or muscovite developed at this time. All the above features are cut by 'friction-breccia' veinlets of quartz, calcite and epidote.

The age of the cataclasis is thus well-defined, but minor late movements probably correspond to the diachronous activity in the Kongsberg area (Starmer 1977). Late cataclasis affected some of the early Vinor intrusions west of a line from Mjovatnet to Huslende (Fig. 2). On the margin of a metagabbro body, about 0.5 km north of Vangestad a thin ultramylonite has lenses of chloritised Vinor amphibolite included in a granulated groundmass. Late epidote and muscovite grew across both ultramylonite and basic lenses. Just to the west, actinolitic metagabbros have protomylonitised bands, but some of these are in composite bodies which just cut the edge of the mylonite zone. Other gabbros further east, towards Lampeland, include cataclastic xenoliths.

In a number of places around Haugesjø (Fig. 6) ultramylonite with microcline porphyroblasts, developed a late, random growth of prismatic hornblende. This phenomenon is particularly characteristic of granitic gneisses in the adjacent Telemark Series. Its origin is not known, but some occurrences are adjacent to exposed metagabbro or amphibolite.

GRANITIC AUGEN GNEISSES

Although, where well-developed, these are rather heterogeneous, granitic augen gneisses, they represent the end-product of the process of microcline porphyroblastesis and variable granitisation seen throughout the mylonite–ultramylonite zone. They contain large microcline porphyroblasts as euhedral crystals or augen, reaching 2 cm or even 3 cm size. Plagioclase porphyroclasts form single or multi-crystal augen. The groundmass consists of fine, granulated quartz and plagioclase (sometimes with later microcline). This is traversed by biotite, which, in a few cases, has partially formed from fine-grained hornblende. The development of these rocks is essentially the same as that of the mylonites. After cataclasis, they had a strong fabric defined by flaser trails of finely gran-

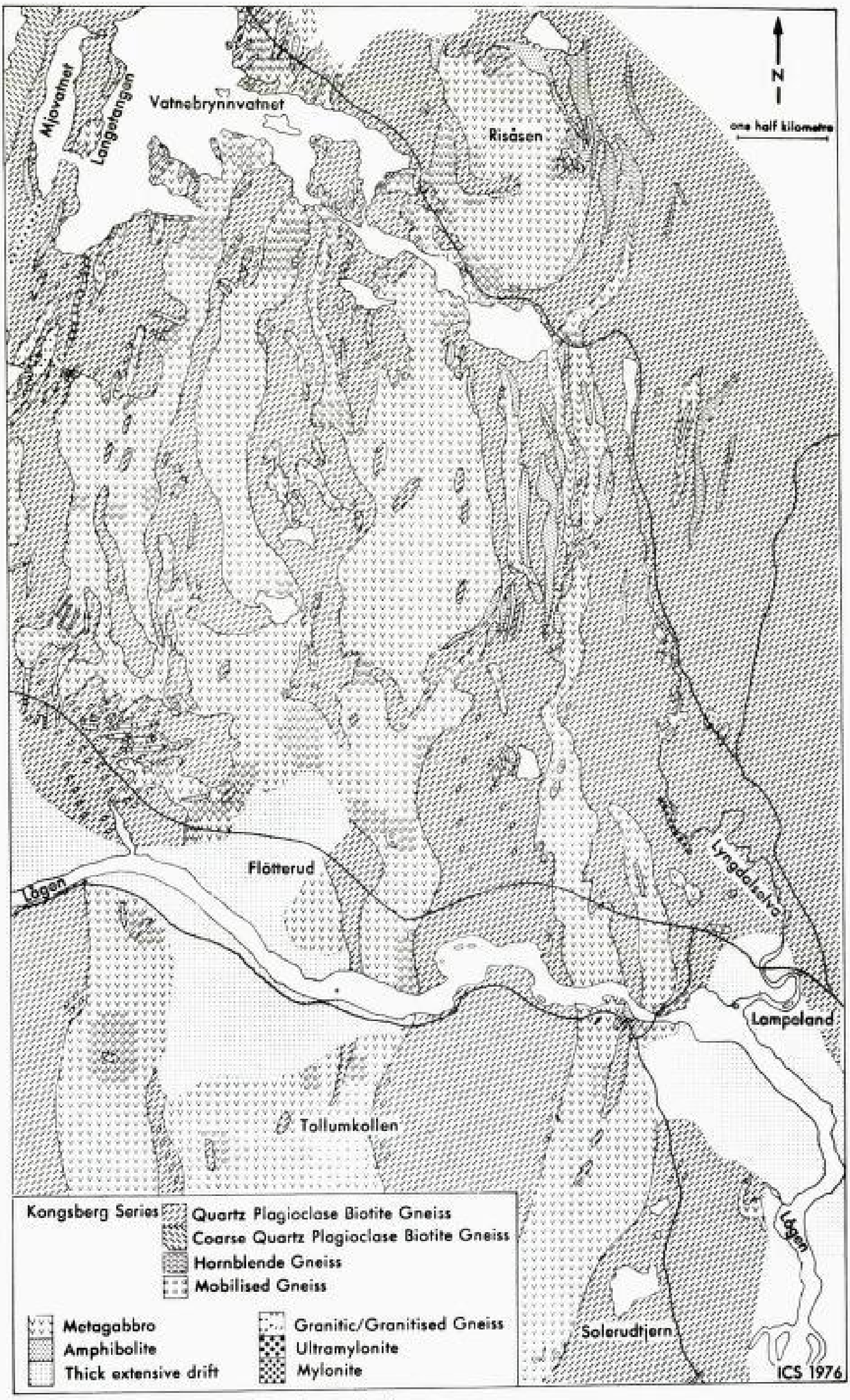

Fig. 4. Lithological map of the Lampeland area.

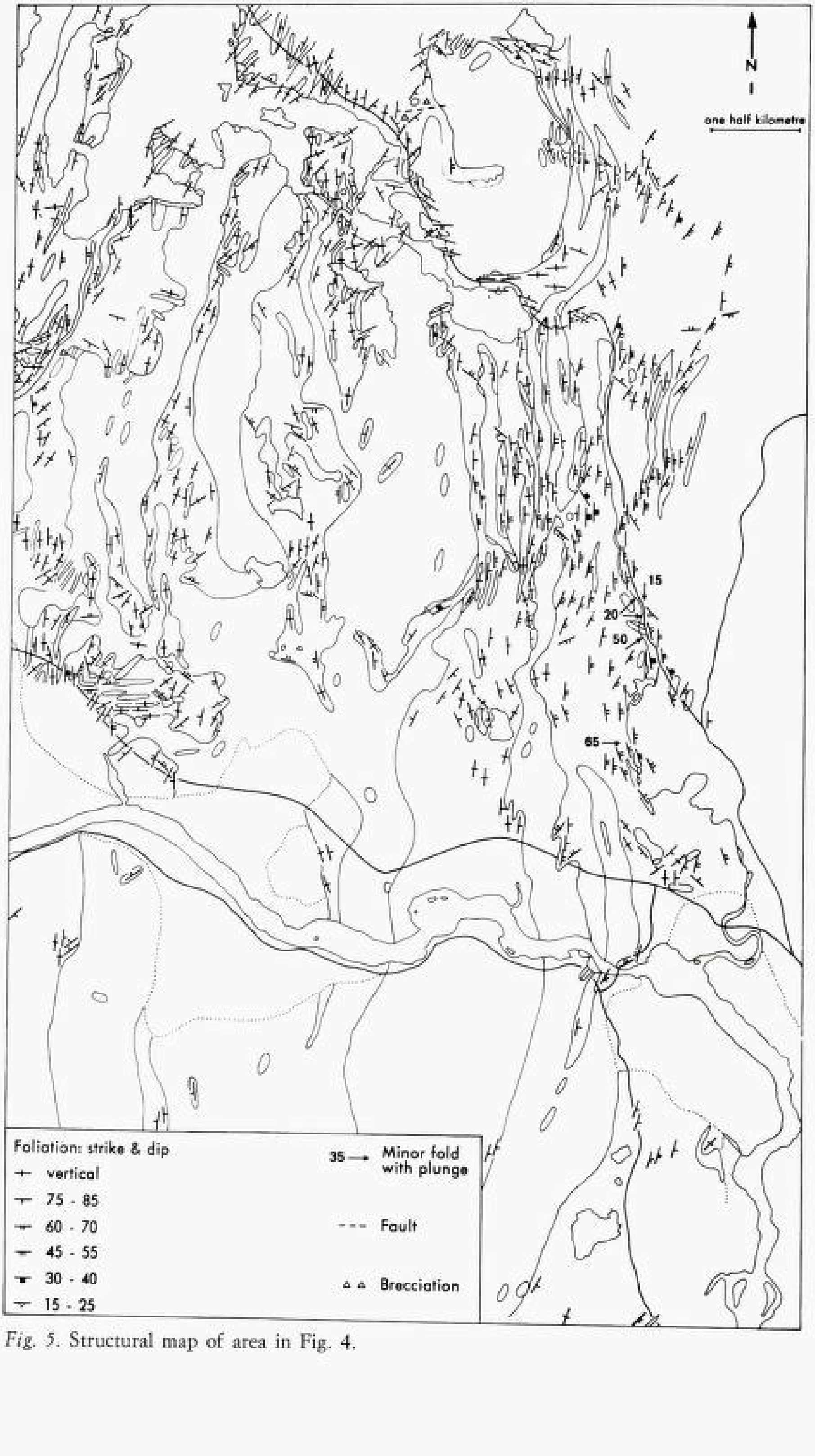

Fig. 5. Structural map of area in Fig. 4.

ulated quartz and plagioclase, often with streaks of biotite. Commonly they had numerous porphyroclastic augen of plagioclase. The microclines subsequently grew in a well-orientated manner, but were also larger and more abundant than in the rest of the mylonite zone. Rarely, microclines in certain bands were slightly granulated or even rolled, but later microcline growths traversed the fabric.

Basic Vinor dykes cut the augen gneisses, but both lithologies are occasionally dissected by thin granitic veins which also cut the Telemark Series amphibolites and are connected with a weak regeneration of granitic rocks and development of pegmatites.

The Kongsberg Series

QUARTZ–PLAGIOCLASE—BIOTITE GNEISSES

These gneisses represent metasediments and possibly some metavolcanics. Cataclasis increases westwards towards the mylonite zone and the rocks are commonly mylogneiss or protomylonite in the western part of the Flesberg–Lampeland tract (Figs. 2–5) and throughout the Haugesjø map area (Figs. 6 & 7).

The gneisses show all modal variations, with some developments of quartz–plagioclase gneiss (± muscovite). Some layers of quartz–plagioclase–hornblende gneiss may be related to intercalated hornblende gneisses. Quartz and plagioclase (oligoclase–andesine) are normally granoblastic or elongate (up to 2 mm size). Biotite forms a lepidoblastic fabric, sometimes partially emanating from hornblende.

A distinctive, coarse protomylonite type forms a discrete, major band, tracing south from Gjømlevatnet across Lågen (Fig. 2). A few thin layers also occur east of this main band. Further north, around Haugesjø (Fig. 6) the coarser and finer types alternate without developing discrete, major units. The coarse types contain sericitised plagioclase porphyroclasts, often developed as augen (0.3–1.0 cm in size). The groundmass commonly consists of flaser trails of finely granulated quartz and plagioclase (0.1 mm size) with ribbons of coarser, recrystallised quartz: biotite occurs in streaks or in clusters with hornblende.

All types of gneiss frequently contain almandine. They also show microcline porphyroblastesis and granitisation. Late fabrics of epidote and recrystallised biotite (± muscovite) occur in many rocks. Rusty 'fahlbånds', produced by disseminations of pyrite and minor chalcopyrite, are noticeably rare in this area compared to tracts further south towards Kongsberg. Their only major development is in the extreme east, between 2 and 3 km north of Lampeland (Fig. 4).

HORNBLENDE GNEISSES

These are part of the supracrustal sequence and are essentially well-segregated, plagioclase-rich amphibolites, although they are quite distinct from the later, Vinor amphibolites. They probably represent intercalated basic volcanics and occur everywhere as thin layers or lenses (usually less than 1 m wide and too small to be shown on the maps). Rarely, much broader irregular bands have somewhat transgressive contacts and interfingering apophyses, suggestive of intrusive relationships.

All types contain green-brown hornblende, andesine and quartz (up to 2 mm size) usually with some biotite. Almandine is common. Retrogressions formed biotite-rich layers and later chlorite, epidote and clinozoisite. These gneisses also contain pyrite (± chalcopyrite) and form part of fahlbånds. They are equivalent to the 'Hornblende Gneisses' unit of the Kongsberg area (Starmer 1977).

The Vinor injections cut all types of gneiss and, even when completely amphibolitised, are noticeably less-segregated and more melanocratic.

MOBILISED GNEISSES

These are extensively developed in the Flesberg–Lampeland area (Figs. 2–5) and formed by mobilisation of the supracrustal gneisses. They are particularly spectacular where they enclose xenoliths of metagabbro or have veined bodies of the latter. Elsewhere, totally within the supracrustals, more acidic (quartz–feldspar-rich) gneisses are mobilised around more mafic bands (hornblende gneisses, biotite-rich layers or fahlbånds) which have either remained intact or broken into lenses. Although there was sometimes a partial assimilation of basic rock and diffusion of margins, contacts often remained sharp. In thin-section, amphibolite and coronite show some marginal assimilation and mixture of minerals, with an increase in biotite content (and enlargement of biotite coronas around iron-ore crystals).

Veins and stockworks of mobilised material have intruded metagabbro, amphibolite and more mafic gneiss. In some cases, several generations of metagabbro and later amphibolitised dykes are all veined. Some later dykes cut through mobilised gneisses, but a few of these have lensed-out along their length. This suggests that the mobility continued, in some places, until after these dykes were intruded, with local variations due to changes in pp H_2O.

The mobilised gneisses are usually white in colour, with grain sizes of 0.5 to 5.0 mm, but occasionally grading to pegmatitic segregations (over 1 cm crystal size) in discrete veins or immediately adjacent to xenoliths. They contain granoblastic quartz and oligoclase–albite, with randomly oriented biotite, but they may become weakly lepidoblastic adjacent to xenoliths or vein margins. Microcline (up to 5 mm size) with good cross-hatching, occurs in varying quantities, but may be entirely absent; where it is more abundant, the gneisses can assume a granodioritic composition. An epidote–biotite fabric, with associated clinozoisite growth in plagioclase, developed after mobilisation and is often lepidoblastic.

In the early stages of mobilisation, networks of thin veinlets (usually 1.0–1.5 mm wide) traverse the rock and often concentrate around xenoliths. The networks contain embayed quartz and sericitised twinned plagioclase with diffuse margins. These crystals are invaded by vermicular, lobate and bleb-like quartz and plagioclase which seem to have generated from them: the blebs (usually 0.02–0.75 mm size) are neither isotropic nor fully ordered and commonly have undulose extinction with dark marginal zones. The blebs also invade biotite and muscovite and the microcline porphyroblasts of granitised specimens.

The mobilised gneisses can be seen to generate gradually from the more acidic supracrustals and are not due to introduced, anatectic material. Increased fluid-vapour activity caused the sweating-out of these segregations from the gneisses under locally increased heat-flow. This thermal upgrading, around the roof levels of the large gabbro body, was overprinted on the regional amphibolite facies conditions. In some cases, almandines have grown across amphibolite and mobilised gneiss junctions and fabrics, reflecting a continuation of these conditions after mobilisation and before the epidote–amphibolite facies fabrics were superimposed.

GRANITIC GNEISSES

In the Kongsberg Series, granitic gneisses and granitised supracrustals (with sporadic augen developments) are related to activity of the same general age as that producing augen gneisses in the mylonite zone. They are concentrated in the west, near the mylonite zone, but occur throughout the area.

These lithologies normally consist of granoblastic quartz and albite–oligoclase, with lepidoblastic biotite and later microcline and microperthite (up to 2 mm size). In some rocks, microcline overprints granulated bands or replaces plagioclase porphyroclasts, giving augen up to 2 cm in size. Late effects include development of epidote and muscovite, saussuritisation of plagioclase and sometimes a new growth of biotite.

The Telemark Series

The Telemark Series differs from the Kongsberg Series in having a much shallower easterly dip and abundant granitic pegmatites. Concentric folds are also more common and often interfere to produce major and minor doming. Amphibolites occur as dykes, but no plutonic bodies were found (akin to the Kongsberg Series metagabbros).

QUARTZ—PLAGIOCLASE-BIOTITE GNEISSES

These gneisses show all modal variations, with minor hornblende in some layers. In the Flesberg area (Fig. 2) they are weakly cataclased towards the mylonite zone, but further north, in the mapped area around Haugesjø (Fig. 6), they are predominantly protomylonite and mylogneiss. In addition, a lithological change northwards from Flesberg to Haugesjø may reflect a different stratigraphical level adjacent to the mylonite zone.

Around Flesberg, the gneisses do not contain augen and are superficially not greatly different from those of the Kongsberg Series, although they are generally slightly coarser (up to 5 mm size crystals) and richer in biotite and epidote. Coarse biotite schists are often developed. Banded gneisses are commonly formed with a series of early biotite amphibolites, which are too small to be shown on the maps. (They would seem to be equivalent, in many ways, to the hornblende gneisses of the Kongsberg Series). The gneisses and biotite amphibolites are variously granitised and sometimes cut by later, intrusive amphibolites.

The mylogneisses and protomylonites of the Haugesjø area, tend to be coarser than the adjacent Kongsberg Series supracrustals (or the Telemark Series around Flesberg). They often have plagioclase porphyroclasts or augen (up to 1 cm size) although these developments are random and sporadic. A very characteristic lithology, with large white augen (reaching 2–5 cm size) is also developed sporadically, but particularly in a belt stretching from the west of Strandvatnet northwards to Haugesjø. The augen are of plagioclase (with subordinate microcline in some specimens) within a fine, granulated groundmass. Layers and lenses of quartz–biotite–plagioclase–hornblende gneiss may represent early amphibolitic rocks (broadly equivalent to the biotite–amphibolites of the Flesberg area). All types of gneiss underwent variable granitisation after cataclasis.

The rocks have a groundmass of quartz and plagioclase which varies from granoblastic to very finely granulated ($<$0.5 mm size) in the more cataclased specimens. The groundmass is traversed by lepidoblastic biotite laths or ragged growths in cataclased rocks. The augen (where present) are aggregates of granulated quartz and plagioclase (often 0.5 mm size) with, or without, a central plagioclase porphyroclast, which has often partially recrystallised to the surrounding smaller crystals, late in the cataclasis. Biotite streaks, bent around these aggregates, produce the augen appearance. In some specimens, shadowy microcline (white in hand specimen) forms single or multi-crystals porphyroblasts and augen, often as patch perthites replacing plagioclase, or as poikiloblasts enclosing granulated groundmass.

GRANITIC GNEISSES AND GRANITIC AUGEN GNEISSES

In the Telemark Series, granitic and partially granitised gneisses are common and formed after cataclasis, although weak shearing occurred later in some. Early biotite amphibolites were partially granitised, but later, intrusive amphibolites cut the granitised rocks and all were deformed by concentric folding. Subsequent minor granitic activity and veining are considered in the following section. Many of the granitic rocks developed late hornblende growths as random, prismatic crystals up to 1 cm length.

The granitic and granodioritic gneisses contain granoblastic quartz, oligoclase and replacive, perthitic microcline (up to 2.5 mm grain size) with isolated biotites defining a weak foliation. Hornblende and muscovite rarely occur and minor components include epidote, sphene and magnetite. In some rocks, microcline overprinted layers of granulated quartz and plagioclase.

In a few places, the granitic gneisses have local developments of microcline and plagioclase augen (up to 1 or 2 cm size) but grade into the only major granitic augen gneiss unit northwest of Strandvatnet (Fig. 6).

GRANITIC PEGMATITES AND GRANITIC VEINS

Granitic pegmatites containing quartz, microcline, plagioclase and biotite

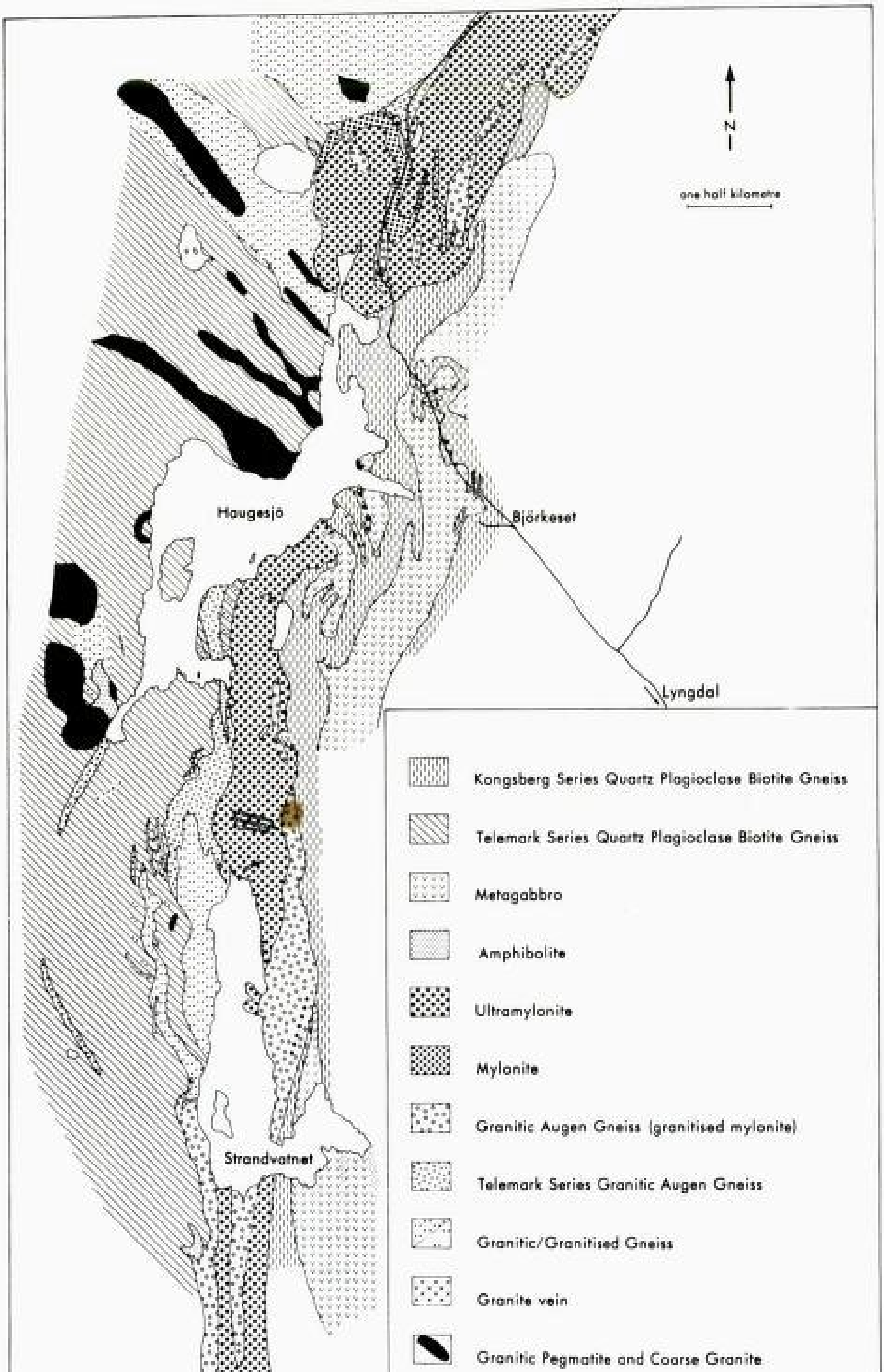

Fig. 6. Lithological map of the Haugesjø area.

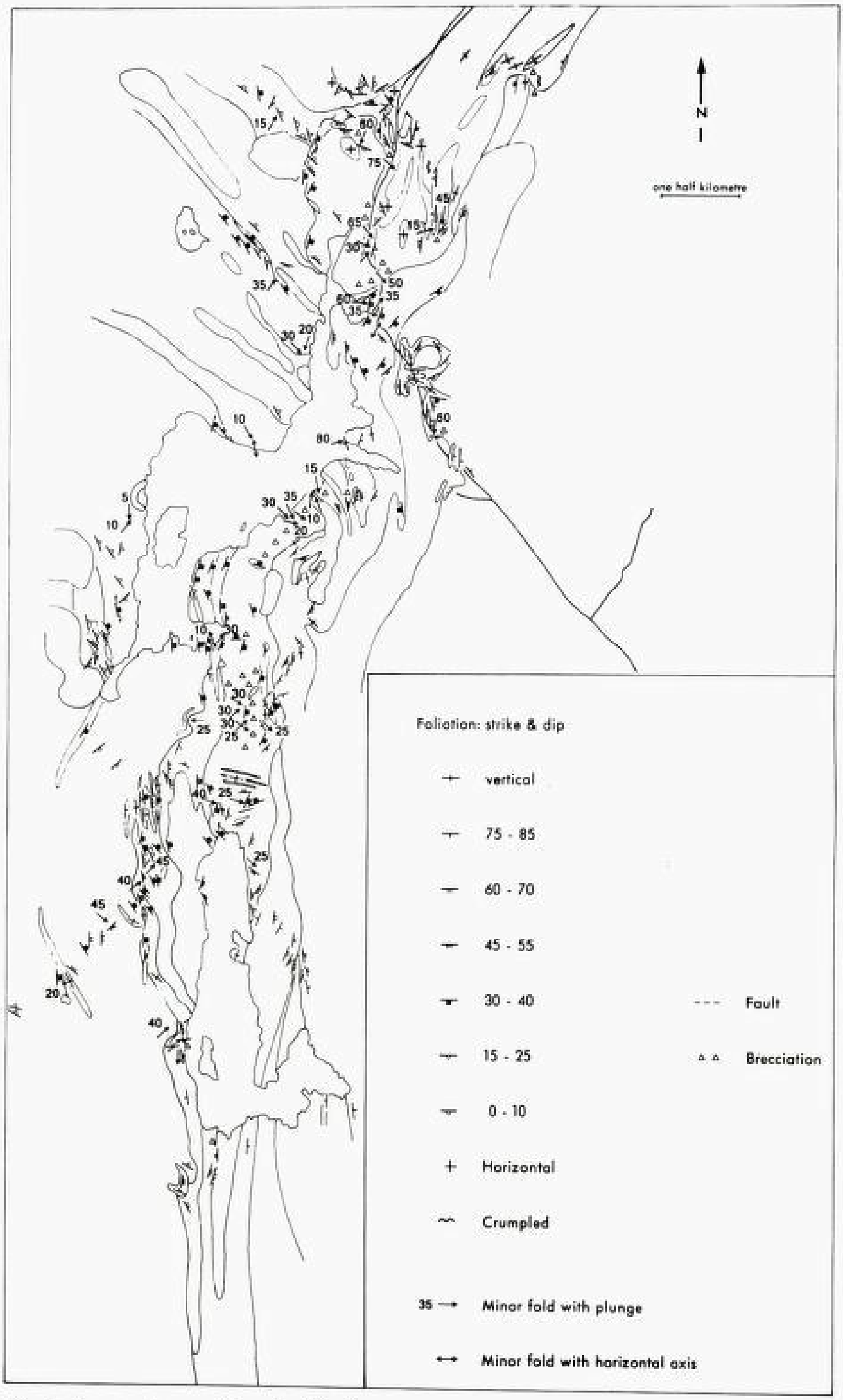

Fig. 7. Structural map of area in Fig. 6.

(± muscovite) cut all rocks in the Telemark Series. They also vein the mylonite zone and granitic augen gneisses. West of Haugesjø (Fig. 6) large outcrops of pegmatite and pegmatitic granite contain xenoliths of cataclased gneisses and of the intruded amphibolites. Around them, supracrustals and granitic gneisses are often soaked in pegmatite veins.

The pegmatites are contemporaneous with a weak regeneration of granitic rocks, giving thin (< 1 cm wide) veins and localised microcline porphyroblastesis, affecting the intruded amphibolites and the concentric folds. Rarely, wider veins have formed. A 5 m wide granite body trends N–S in Telemark gneisses (developed here as the type with large plagioclase augen) just northwest of Strandvatnet. This has small apophyses, but its contact is concordant to the foliation in the gneiss and the granite itself has developed a weak fabric near its margin.

The intruded gabbros and amphibolites

The 'Vinor' intrusions of the Kongsberg Series and the amphibolitised dykes of the Telemark Series are grouped together in this description since they belong to the same general period of basic injections.

VINOR METAGABBROS AND AMPHIBOLITES

The Vinor intrusions represent a series of basic injections into metamorphosed and cataclased supracrustals. They were subsequently partially amphibolitised, particularly in the east, but still often preserved their igneous textures. A number of injections can be distinguished, but across the area as a whole three distinct phases are separable. These are now represented by (i) early olivine gabbro and olivine norite coronites, (ii) later coarse metagabbros and (iii) a separate phase of finer grained, heavily amphibolitised dykes.

The earliest intrusions of olivine gabbro and olivine norite (usually 5 mm grain size) commonly have ophitic textures, with corona growths around mafics and andesine rims on the original labradorite-bytownite laths. The rocks are melanocratic, often with a purple coloration which is also common in the Bamble coronites (or 'hyperites') where it has been attributed to dust inclusions in the feldspars (Starmer 1969). More intensive metamorphism of these bodies formed metagabbros consisting of actinolite or actinolitic hornblende (often as felted masses almost completely replacing pyroxenes) and granoblastic andesine (sometimes with relict cores of labradorite-bytownite). All the plagioclases are saussuritised, concomitant with a growth of chlorite and epidote in the rest of the rock. Late retrogressions in some have caused complete diapthoresis to greenschist assemblages.

A second set of intrusions is now represented by more felsic, green-coloured metagabbro with a coarse, decussate growth of hornblende, actinolite and andesine. In some the plagioclase is purple. Grain size is usually greater than 5 mm. Widespread felsic segregations are developed and, in a few cases, these may have resulted from contamination by mobilised gneiss. This second phase of intrusions often veins the earlier coronites and may enclose xenoliths with both sharp and diffuse margins, suggesting that the earlier gabbro was not totally consolidated during incorporation.

Towards the mylonite zone (particularly west of a line from Mjovatnet to Huslende – Fig. 2) more felsic metagabbro is more common and parts of the bodies show effects of very late cataclasis and weak granitisation. A few dioritic patches occur, but they are not as extensive as in areas further south, close to the Kongsberg Series margin. Although the bodies are cataclased in some parts, they also cut the edge of the main mylonite zone. They are composite masses which combine intrusions of both the first and second phases. Further east (between Flesberg and Lampeland and east of Haugesjø) other composite bodies, comprising both first and second phase intrusions, contain cataclased xenoliths. Apart from the isolated occurrences of late cataclasis in the west (mentioned above) the large gabbroic bodies generally have a post-tectonic form and cut cataclastite fabrics throughout the area.

The third, late phase of finer-grained, heavily amphibolitised intrusions is represented by small bodies, many of which cannot be shown on the maps. They usually occur as thin dykes or concordant sheets (10 cm to 0.5 m wide) and their fine grain size (usually $<$0.5 mm) has facilitated severe amphibolitisation, even during waning metamorphism. Rarely, they contain small ($<$3 mm) almandines. The dykes frequently cut the earlier metagabbros and dissect mobilised gneisses with incorporated metagabbro xenoliths. Often, intrusion trends through metagabbros are controlled by the foliation of the surrounding gneisses. Some dykes which cut mobilised gneisses are lensed-out further along their length. Occasionally, two generations of these dykes can be seen in supracrustals and mobilised gneisses.

The amphibolitised dykes cut discordantly through granitised mylonites and their associated augen gneisses. A spectacular example of this is seen just west of Svarttjern (Fig. 2) where small apophyses inject around and between microcline porphyroblasts. A very weak and late phase of granitic veining in pluton margins and amphibolite dykes has already been discussed.

The amphibolites carry nematoblastic green-brown hornblende, with granoblastic andesine, quartz and late epidote ($\pm$biotite). Some contain remnant labradorite laths. Occasionally crushing is accompanied by complete chloritisation.

The major gabbro bodies (Figs. 2–7) are usually composite, derived principally from the first and second phases of intrusion. Although they show a tendency to elongation, parallel to the regional structure, their complex outcrop patterns represent protrusions from a much larger mass at depth. Supracrustal roof pendants have complex and interfingering margins. The large mass at depth is probably the northern end of the huge 'Vinoren' body, which is exposed for some 8 km south of Lampeland (Bugge 1937). Within the present area, the main mylonite zone marks the western limit of large gabbros outcrops. In the east, they also disappear; north of Lampeland, several small gabbro outcrops occur in Lyngdalselva but not at a slightly higher level in the adjacent road, suggesting that the large gabbro mass may be at greater depths in that area.

Mobilised gneisses are extensively developed in the east, but are less common towards the western mylonite zone in the Flesberg and Haugesjø areas. Surveys around the southern end of the large 'Vinoren' body (at Dronningkollen, some 8 km south of Lampeland) have shown developments of mobilised gneiss with xenoliths of metagabbros and fahlbånds. The mobilisation, therefore, is associated with the roof of this huge gabbro mass. The gneisses involved are more acidic than many supracrustals in other parts of the Kongsberg Series and their plastic behaviour probably facilitated the relatively passive emplacement of this large basic body and the development of some globulithic features. Their mobility resulted from increased fluid-vapour activity and a greatly increased heat flow associated with the gabbro uprise, but not emanating entirely from the cooling magma. The gneisses were mobile when some of the earlier gabbro intrusions were partially or totally consolidated. The gabbros were held at high subsolidus temperatures for a prolonged period and cooled very slowly under elevated metamorphic conditions. The coronite pyroxenes often show some exsolution features which, in some places, became extreme (e. g. at Tollumkollen, south of Lågen – Fig. 4).

TELEMARK SERIES AMPHIBOLITES

The Telemark Series has numerous, thin, intruded amphibolites, but in the mapped areas they never develop the plutonic forms found in the Vinor intrusives of the Kongsberg Series. They resemble the amphibolitised, late Vinor dykes and sheets cutting Telemark gneisses, granitic gneisses and the mylonite zone. They may represent several intrusive phases, since some, which are mildly sheared and biotite-rich, are adjacent to unsheared bodies. Late injection of granitic pegmatites and thin granitic veins into these amphibolites has been discussed previously.

The amphibolites generally have nematoblastic green-brown hornblende (up to 3.5 mm size) with granoblastic quartz and saussuritised andesine (usuallly up to 2 mm size). Biotite follows the fabric and is partially retrograde from hornblende. In sheared rocks, it may form sheaves (up to 6 mm size) of acicular biotite and remnant hornblende. Extreme retrogression has produced greenschist facies assemblages. Some amphibolites have a late, random overgrowth of large hornblendes (up to 2 cm size) possibly related to similar developments in granitised gneisses and ultramylonites.

Structure of the area

The Kongsberg Series structurally overlies the mylonite zone and the Telemark Series. The regional foliation and lithobanding strike N–S with an easterly dip which decreases from east to west, through the Kongsberg Series and mylonite zone into the Telemark Series. This is complicated in the Haugesjø area (Figs. 6 & 7) by concentric cross-folding in the Telemark Series and by the development of a complex basin in the ultramylonite.

The earliest foliation observed in the Kongsberg and Telemark gneisses is a penetrative fabric parallel to the lithobanding, which is considered to represent transposed bedding. Sporadic development of asymmetric, intrafolial, shear folds (within non-cataclased rocks) may result from this process.

Later, almost coplanar cataclastic fabrics overprinted the gneiss foliations, particularly in the west, towards the mylonite zone. All the above structures were locally deformed around the subsequent Vinor intrusions, partly during their emplacement and partly during a later phase of concentric folding.

A few isolated, minor folds post-date the intrusion of the Vinor and Telemark amphibolites, but pre-date a phase of regional concentric folding. These tight to sub-isoclinal shear folds (usually <1 m wavelength and amplitude) have moderate to shallow plunges to the south and occasionally deform some intruded amphibolites without affecting adjacent dykes. On the Langetangen peninsula in Vatnebrynnvatnet (Figs. 2–5) the shear folds are deformed by N–S concentric folds.

Open, concentric folds on subvertical axial planes developed after the intrusion of most Vinor bodies and Telemark amphibolites, but before the injection of granitic pegmatites. These structures formed on NE–SW and NW–SE axes (which were sometimes more N–S and E–W, particularly near resistant gabbros): they occurred as minor folds throughout the area, but also developed as major structures and were most intensive in the Telemark Series, becoming more sporadic and open in the mylonite zone and less common in the Kongsberg Series.

Concentric cross-folding was most strongly developed in the north, around Haugesjø, where it produced domes and basins on all scales and helped to form the major bend in the Kongsberg Series margin. Figs 6 and 7 show a major, open basin in ultramylonite to the north of Haugesjø: this is a complex structure (with shallow plunging, minor cross-folds) and is located immediately north of a discontinuity in the ultramylonite zone. A major structure, complementary to the basin, occurs just to the north, in the Telemark Series. The combination of the discontinuity in the main mylonite zone with these structures formed the only major bend in the Kongsberg Series western margin. Further south, in the Flesberg area, effects were less marked with isolated, minor folds (usually without cross-folding) and gentle flexuring of the mylonite belt on a major scale. Local deformation occurred around protruding gabbros and west of Fløtterud (Fig. 4) a large flexure has associated minor folds which deform some Vinor dykes but are cut by others. A concentration of open concentric folds and domes occurs along Lyngdalselva, about 1.5 km north of Lampeland (and about 5 km east of the mylonite zone).

Where cross-folding produces doming, the two sets of interfering structures usually seem contemporaneous, but rarely folds with NE–SW axes deform those on NW–SE axes. This is seen both to the north of Lampeland and in the Haugesjø area. Wavelengths range upwards from 20 cm and the respective amplitudes are much smaller. The style and tightness varies, to some extent, with lithology and previous structure. Axial plunges are commonly low to moderate to the NE or SE, being largely controlled by the pre-existing easterly layer dip. A few folds in the Kongsberg Series are markedly asymmetric (up to 5 m amplitude) with NE–SW to N–S axes and steep axial planes: vergences suggest an upward westerly movement of the eastern side. Isolated recumbent folds of the same phase deform Telemark amphibolites west of Neset (Figs. 2 & 3) and affect the eastern side of the ultramylonite zone between Haugesjø and Strandvatnet (Figs. 6 & 7).

The 'friction breccia' movements and later faulting

Brittle fracture phenomena corresponding to the 'friction breccia' movements of A. Bugge (1928, 1937) are developed randomly over a wide area, in and around the mylonite zone. The brecciated fractures are not continuous and are not of regional significance in separating the two complexes: they result from a number of tectonic events, including intensive developments of conjugate jointing on concentric flexures (particularly extensively developed in the ultramylonite between Haugesjø and Strandvatnet — Figs. 6 & 7).

Where discrete, well-defined fault planes are observed, they often post-date the main brecciation. The faults vary somewhat in orientation, but generally strike N–S to NW–SE and dip steeply east. Where definable, the displacements show a consistent pattern, being reverse to oblique and more rarely dextral strike-slip (with the eastern sides moving upwards and/or southwards). The strike-slip faults occur throughout the area (e.g. west of Landetjern, on the southwest side of Risåsen and along the west shore of southern Haugesjø) and may represent a separate displacement to the oblique-reverse faulting. A few random shear planes around gabbro margins have no coherent pattern.

Retrogressions associated with the brecciation and faulting show lower to middle greenschist facies assemblages. The 'friction breccias' are commonly accompanied by hydrothermal veins, developed on all scales from microscopic to 20 cm width and containing quartz, calcite and epidote (either alone or in combination). In some cases, pure epidote veinlets are cut by calcite veinlets. Late stage drusy quartz occurs locally.

The 'friction breccias' and veins transect all rocks and structures, including the pegmatites, the concentric folds and the ubiquitous saussuritisation. Examples of disoriented xenoliths of granitised ultramylonite within 'friction breccia' veins, show clearly the separation of syn-metamorphic cataclasis and post-metamorphic brecciation. Many of the 'friction breccia' movements were concentrated around the mylonite zone because of the relatively planar and brittle nature of this belt of instability at the junction of the Kongsberg and Telemark Series. Brecciation of the same age also occurs in restricted zones throughout the area.

Summary

In the present area, the boundary between the Telemark and Kongsberg Series is a zone of mylonite and ultramylonite which is granitised in places to form augen gneisses. The boundary is not the so-called 'friction breccia' which is the result of brittle fracturing developed long after the syn-metamorphic cataclasis.

The only major bend in the Kongsberg Series margin occurs in the present area. It resulted from the development of a major basin in the mylonite zone, with complementary structures in the Telemark Series. It was located at this point because of a tectonic break in the mylonite zone and because this area may have been a locus of instability between the huge Vinoren gabbro to the south and large gabbros to the north around Lauvnesvatnet (Starmer, in prep.). The mylonite zone was also thinner and less steeply inclined at this point.

From the foregoing descriptions and discussions, the sequence of events in this area is as follows:

(1) The Kongsberg and Telemark Series consisted of supracrustals (metasediments and basic volcanics) which underwent middle to upper amphibolite facies metamorphism and developed a penetrative foliation.

(2) A complex upthrust of the Kongsberg Series (at middle to upper amphibolite facies grade) produced a major mylonite zone along the junction with the Telemark Series.

(3) Granitic activity confined largely to the Telemark Series, caused ubiquitous microcline porphyroblastesis in the mylonite zone and sporadic developments of granitic augen gneiss (at middle to upper amphibolite facies).

(4) Several intrusions of 'Vinor' gabbro produced composite plutonic bodies (including the large Vinoren body) in the Kongsberg Series. The earliest injections (in the west) were slightly cataclased by late movements and weakly granitised but later ones include granitised cataclastite xenoliths. Metamorphic conditions were middle to upper amphibolite facies and acidic gneisses were mobilised by increased heat flow around the large gabbro mass, a mobilisation which partially overlapped stage (5).

(5) The late Vinor dykes and sheets and the Telemark amphibolites were then emplaced (middle to upper amphibolite facies); these cut the mylonite zone.

(6) Major and minor concentric folding, on two axial trends, produced domes and basins and caused the major bend in the Kongsberg Series margin at at point where there was a tectonic break in the mylonite zone.

(7) Granitic pegmatites invaded the Telemark Series and the mylonite zone. Thin granitic veins probably represent a weak regeneration of granitic rocks.

(8) Prolonged metamorphism at epidote amphibolite facies produced overprints of epidote, clinozoisite, biotite and muscovite in all rocks.

(9) Brittle-fracture ('friction-breccia') movements at lower to middle greenschist facies were followed by hydrothermal veining. Late faults show a consistent displacement pattern, with the eastern side moving upwards and/or southwards.

Many of the stages in this sequence are shown particularly well within a very small area on the east shore of Haugesjø (Fig. 6). Metagabbro there intrudes granitised ultramylonite (with inclusion of xenoliths) and is cut by amphibolitised dykes. Interbanded ultramylonites and amphibolites have been folded about subhorizontal NNE and NW axes and all lithologies and structures are cut by granitic pegmatites. Later 'friction breccia' veins cut all rocks.

The two complexes were effectively welded together at the end of the thrusting and cataclasis and subsequently had a common history, although granitic activity and later pegmatites were concentrated in the Telemark Series and plutonic gabbros in the Kongsberg Series. The relative age of the cataclasis is well-defined and the overall displacement was an upthrust of the Kongsberg Series, but it involved a series of movements. Work is now in progress on the continuation of the mylonite zone and on fabric analysis of the movement directions.

If the large Vinoren gabbro of Bugge (1937) is one entity, it is exposed intermittently over a N–S distance of 13 km and an E–W width of up to 3 km. Its size and the extent of mobilised gneisses around it, both reflect a zone of increased heat flow and fluid-vapour activity. The evidence of prolonged cooling of the gabbro also supports the idea that the magma was not the sole source of the increased heat flow. Gabbro bodies extend westwards in the Kongsberg Series to the mylonite zone, although later dykes cut through it and are also represented in the Telemark Series. The gabbros pierced exposed levels at the end of the upthrusting which produced the cataclasis and show some tendency to more felsic compositions near the mylonite zone. All of these features suggest a connection between the upthrusting, the gabbro intrusions and the greatly increased heat flow. The granitic activity at the end of the cataclasis may also be linked to high regional heat flow and anatexis at depth. Thus, the present area displays evidence of a number of major petrological and tectonic processes which are linked to large-scale crust-mantle interactions in the Proterozoic.

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