# On the structure of a high-grade metamorphic Precambrian terrain in Rogaland, south Norway

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Largely with the aid of thinly layered 'garnetiferous migmatites' which show small-scale folding and could be used as marker horizons, three complicated structures were unravelled in the area: in the northwestern part a very large refolded isoclinal antiform, in the central part a dome-like structure, and in the southeastern part a large isoclinal fold, refolded into a reclined structure. Several deformation phases can be recognized from further analysis of these structures, the first of which ($D_1$) produced a 'new' litho-tectonic layering. Subsequent deformation gave rise to very large, isoclinal to open folds, which constitute the main structures of the area.

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An area of about 150 square kilometres in the high-grade metamorphic Precambrian terrain of Rogaland, south Norway, has been mapped by the authors for both petrological and structural purposes (Fig. 1), the northwestern part by Kabel, the central part by Steenstra, and the southeastern part by Huijsmans.

Almost all previous mapping work in this part of south Norway, e.g. Michot (1970) and Hermans et al. (1975), has emphasized petrological aspects.

For structural studies the reader is referred to Michot (1960) and Falkum (1966, 1976).

This paper will deal mainly with structural aspects of the area. The authors have tried to reconstruct a three-dimensional model demonstrating the style of deformation. A number of successive deformation phases is proposed to explain the structures.

The nomenclature as used in this paper for rocks and formations is according to Hermans et al. (1975).

## Petrography of the mapped area

The mapped area, part of a Precambrian granulite-facies terrain, is mainly made up of charnockitic and garnetiferous migmatites (Fig. 2).

The charnockitic migmatites are characterized by the regular occurrence of leucocharnockitic components. The migmatites have been divided into mainly layered and mainly massive parts. The distinction is defined by the relative abundance of mesocratic layers. In the layered migmatites the layering is regular and rather continuous.

The leucocratic charnockitic rocks, which are medium to coarse grained, consist mainly of quartz, perthitic orthoclase, plagioclase ($An_{25-35}$), hypersthene, and minor amounts of biotite and magnetite/ilmenite. Garnet occurs sporadically.

The mesocratic, noritic to enderbitic layers which are fine grained, consist mainly of plagioclase ($An_{40-65}$), hypersthene, diopsidic clinopyroxene, and minor amounts of quartz, biotite, and magnetite/ilmenite.

The garnetiferous migmatites are mainly made up of thin garnet-, cordierite-, sillimanite-, and spinel-bearing layers (melanosome), alternating with leucocratic, garnet-bearing granitic layers (leucosome). Apart from the mentioned minerals, the garnetiferous migmatites contain quartz, perthitic orthoclase, plagioclase ($An_{25-40}$), and minor amounts of graphite. Cordierite-, hypersthene-, garnet-, and spinel-bearing granofelsic layers occur sporadically. In some samples the spinel is pseudomorphous after sapphirine. Thin quartzitic and noritic layers within the garnetiferous migmatites occur occasionally.

The textures of the charnockitic and garne-

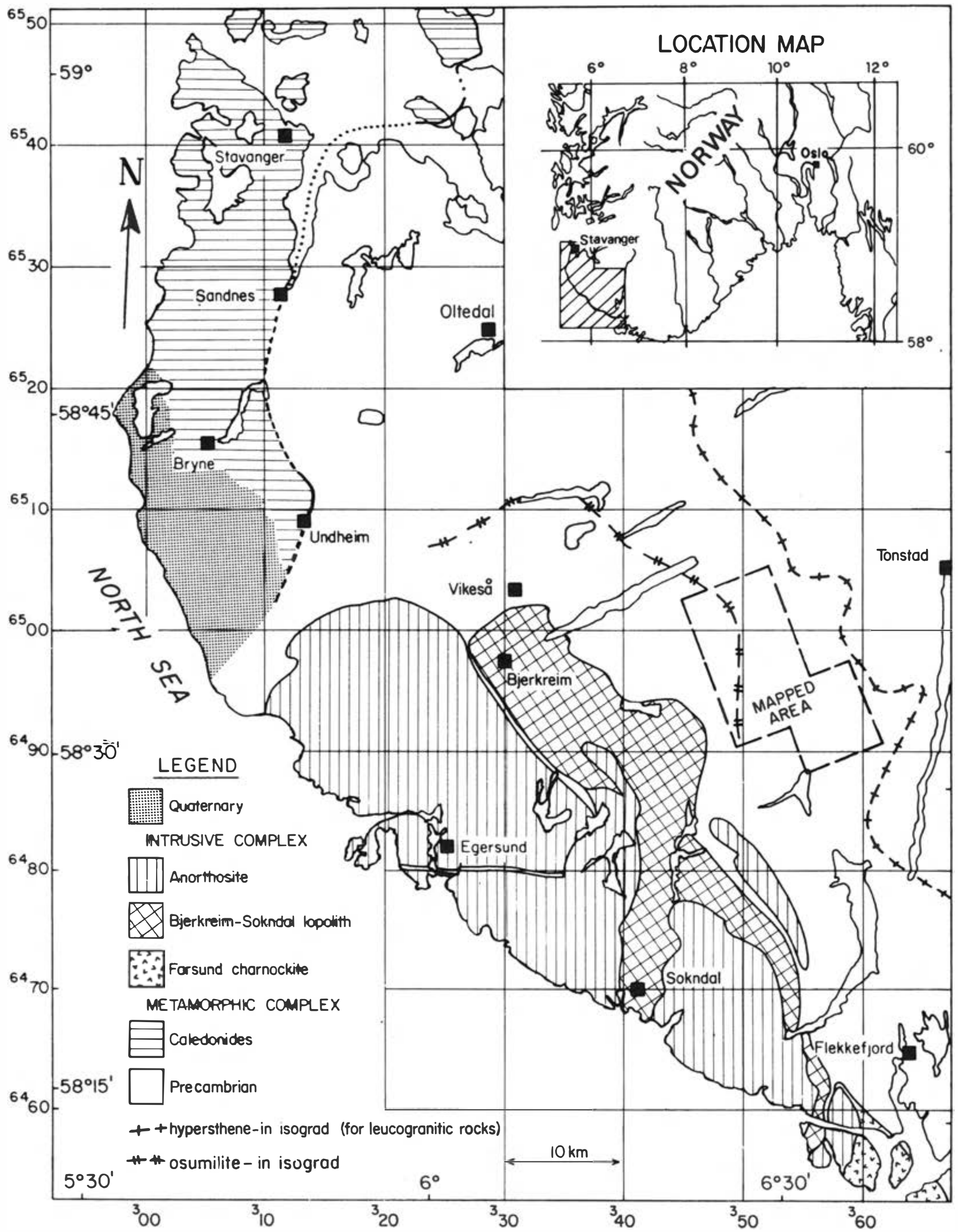
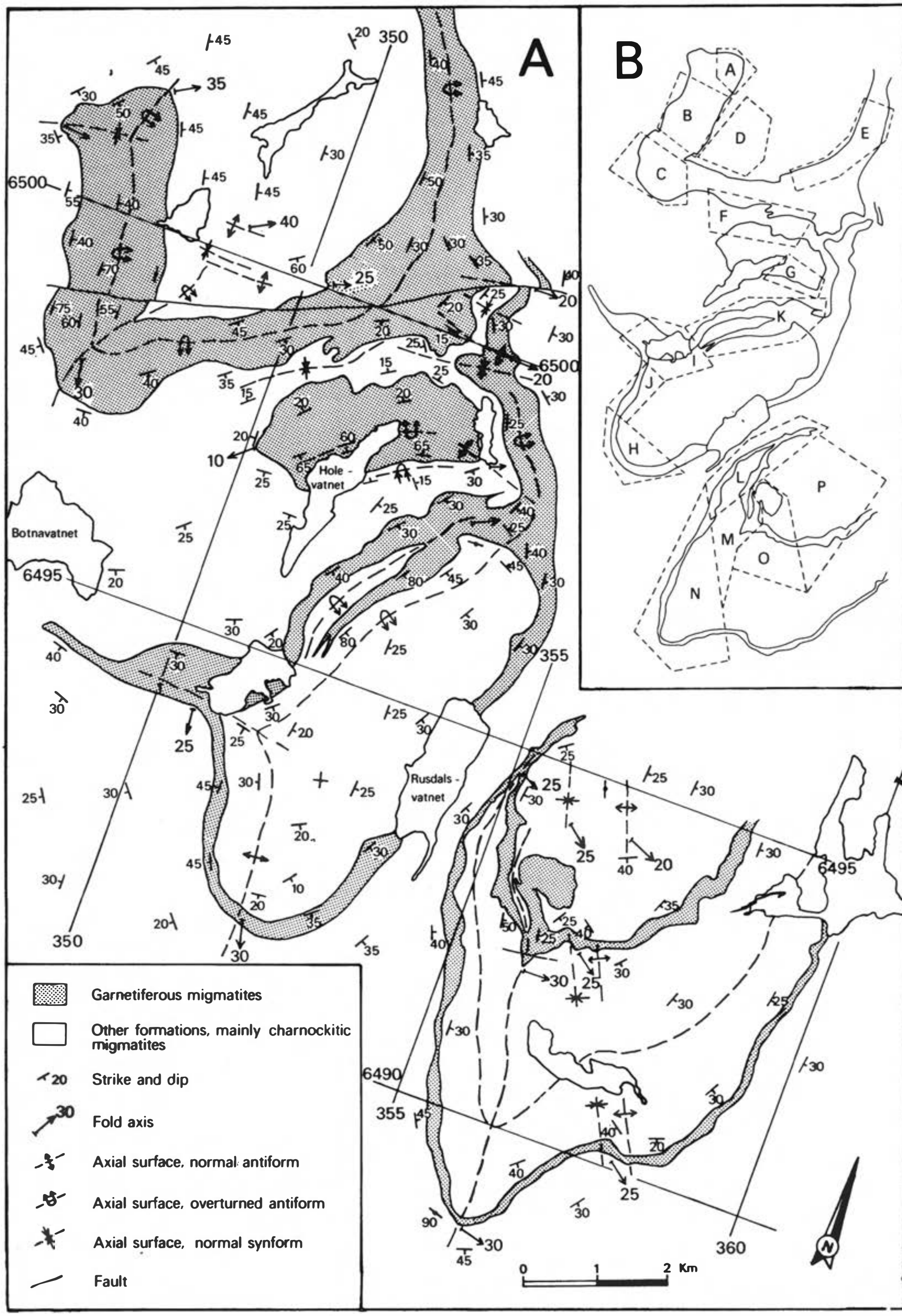



*Fig. 1.* Simplified geological map of south Rogaland and the location of the mapped area.

*Fig. 2A.* Simplified geological map of the area around Gyadalen and Rusdalen, Rogaland. Gridlines area taken from the Norges geografiske oppmåling 1:50,000 map. B. The mapped area divided into domains.


A
B
Botnavatnet
Hole-vatnet
Rusdals-vatnet
6500
6495
6490
350
355
360
0 1 2 Km
Garnetiferous migmatites
Other formations, mainly charnockitic migmatites
Strike and dip
Fold axis
Axial surface, normal antiform
Axial surface, overturned antiform
Axial surface, normal synform
Fault
A
B
C
D
E
F
G
H
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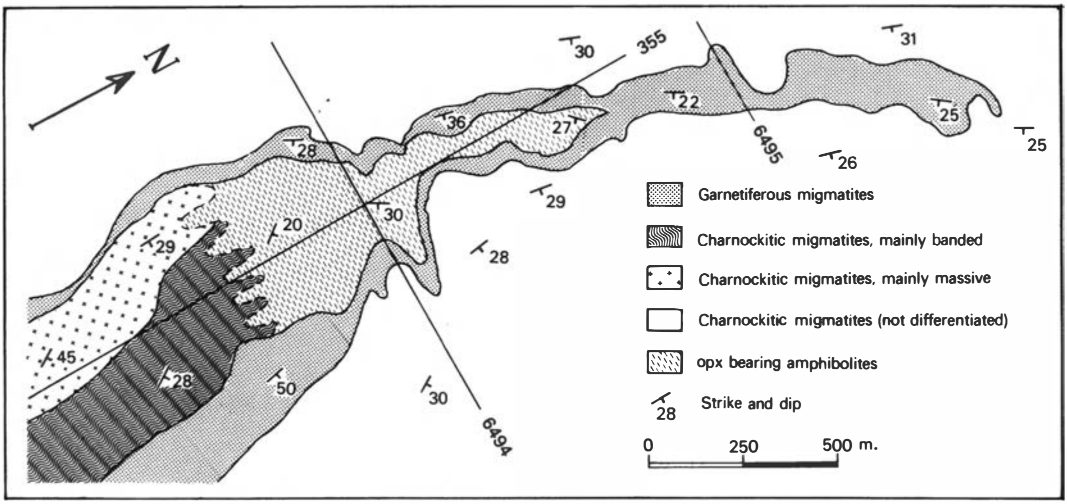


*Fig. 3.* Map of area around domain L showing the foliation of charnockitic migmatites and amphibolites oblique to lithological boundaries.

tiferous migmatites are granoblastic, although a preferred orientation of the minerals biotite and sillimanite is often present.

East of Botnavatnet a concordant body of two-clinopyroxene granite, ± fayalite, is intercalated within the charnockitic migmatites (Rietmeijer 1979).

A WNW-trending doleritic dike transects the mapped area.

## The origin of the layering in the migmatites

The mineralogical composition clearly demonstrates that the garnetiferous migmatites represent metapelitic sediments (Dietrich 1960, Hermans et al. 1975). However, primary sedimentary structures could not be demonstrated.

Within the garnetiferous migmatites isoclinal intrafolial folds of thin quartzitic and noritic layers can be found. At one locality an apparently undeformed noritic intercalation was found to be an accumulation of more than 30 isoclinal folds with a total thickness of only 65 centimetres.

Locally the foliation as defined by thin compositional layering as well as a distinct mineral foliation is oblique to lithological boundaries, as can be seen in the field, especially in the charnockitic migmatites of the southeastern part of the area (Fig. 3). These observations seem to indicate that the actual layering is, at least partly, a result of transpositional folding and possible contemporaneous shearing.

Besides the development of a transpositional foliation, metamorphic differentiation must have played an important part in the origin of the layering. The mesocratic parts of the garnetiferous migmatites which include rootless isoclinal folds as tectonic relicts, are interpreted as paleosome. The leucocratic, sometimes garnet-bearing rocks are interpreted as magmatic parts of the migmatites, formed under high-grade metamorphic conditions. The foliation of these leucocratic rocks, defined by a weak preferred orientation of the constituent minerals, is parallel to the foliation in the paleosome. In general the contacts between magmatic and non-magmatic parts are parallel to the foliation.

The consequence of the development of a transpositional foliation is that orginally large and continuous (pelitic) sedimentary horizons now are thickened or thinned and possibly disrupted, forming new litho-tectonic layers.

The garnetiferous migmatites as exposed in the northwestern, central, and southeastern part of the mapped area should be considered as three different litho-tectonic levels.

# Description of the structures in the area

The thin-layered nature of the garnetiferous migmatites makes them very suitable for detailed structural observations, in contrast to the charnockitic migmatites. The layering is often intensely folded; the size of the folds varies from centimetres to several metres. An axial-plane foliation is generally lacking. Locally a mineral lineation of hypersthene, sillimanite, or quartz can be found.

Overprinting relationships of minor folds in outcrops are difficult to recognize. The relationships only become clear on the scale of the map. To unravel the complicated structures, the mapped area was divided by trial and error into domains that were analysed with the aid of equal-area projections of poles to foliations, poles to axial surfaces, and minor fold axes. The most important domains and their corresponding stereographic projections are shown in Figs. 2, 4, and 5.

In general, minor folds could be divided into two different style groups: isoclinal intrafolial folds and more open folds. We adopted the working hypothesis that minor folds of a certain style are related to a major fold of the same style in a chosen domain. A comparison of poles to foliation diagrams with minor fold axes' diagrams from the same domains proved that this working hypothesis was not unreasonable.

The technique of using Z- and S-asymmetries was successful for interpreting the structures of domains G and K (Fig. 2).

The model of successive events of deformation presented below is mainly derived from the outcrop pattern as well as from the data shown in the stereographic projections.

A description of the major structures in the northwestern, the central, and the southeastern part of the mapped area is given below:

## *The northwestern part*

The outcrop pattern of the garnetiferous migmatites in the northwestern part can be explained as a large refolded tight antiformal structure (Figs. 2 and 6). In domain A the axial surface dips ca. 40°E; the fold axis plunges ca. 35°ENE (Fig. 4-a, b, c). Minor folds are not constant in orientation due to subsequent deformation (Fig. 4-c). Further south the fold axis of the major fold probably trends N-S, subhorizontal, as is indicated by minor folds in this area (Fig. 4-d). Within domain C, refolding of the tight antiformal structure resulted in an open antiform with an axial surface which dips ca. 45°ESE and a fold axis which plunges ca. 30°S (Fig. 4-e, f, g, h, i). To the northeast the refolded tight antiformal structure strikes NE and further northwards N (Fig. 4-j); the fold axis is probably sub-horizontal.

Because of an open ENE-trending synformal structure (Fig. 4-k) the garnetiferous migmatites outcrop again around the northern part of Holevatnet. The axial surface of this synform is almost vertical; the fold axis is sub-horizontal.

The outcrop pattern of the garnetiferous migmatites near Holevatnet itself can be explained as a double plunging antiform with a NNW dipping axial surface. West of the lake the fold axis plunges ca. 10°SW; further eastnortheast the fold axis plunges ENE (Fig. 4-l, 5-a).

At several localities the occurrence of open folds with steep E trending axial surfaces indicates a later superimposed folding.

## *The central part*

The outcrop pattern in the central part of the area can be described as an elongated dome-like structure with its long axis trending NNE-SSW. The SE and S limbs dip outward at moderate angles defining a fold axis plunging 20°S (Fig. 5-b).

The SW limb dips ca. 45°SW; the NW limb dips ca. 40°SE, joining the former by forming a tight to isoclinal reclined fold, which causes foliations to strike E-W and dip ca. 20°S (Fig. 5-c). The fold axis plunges ca. 20°S as can be measured from tight minor folds (Fig. 5-d). In this area quartz rods have the same orientation.

The NW limb of the dome joins the NE limb, forming a tight to isoclinal fold, which results in a single layer, that strikes NNW and dips ENE. East of the described NW limb of the dome, another layer is present, which dips steeply ESE and disappears to the SSW. With the aid of S- and Z-asymmetries, this layer can be interpreted as an isoclinal synform. Fold axes of tight minor folds plunge ca. 20°NE (Fig. 5-e).

The disappearance of the layer to the SSW is probably caused by boudinage. Another possibility is that the trough line of the synform is tilted above the topography in south-southwestern direction. Local field observations favour the first interpretation.

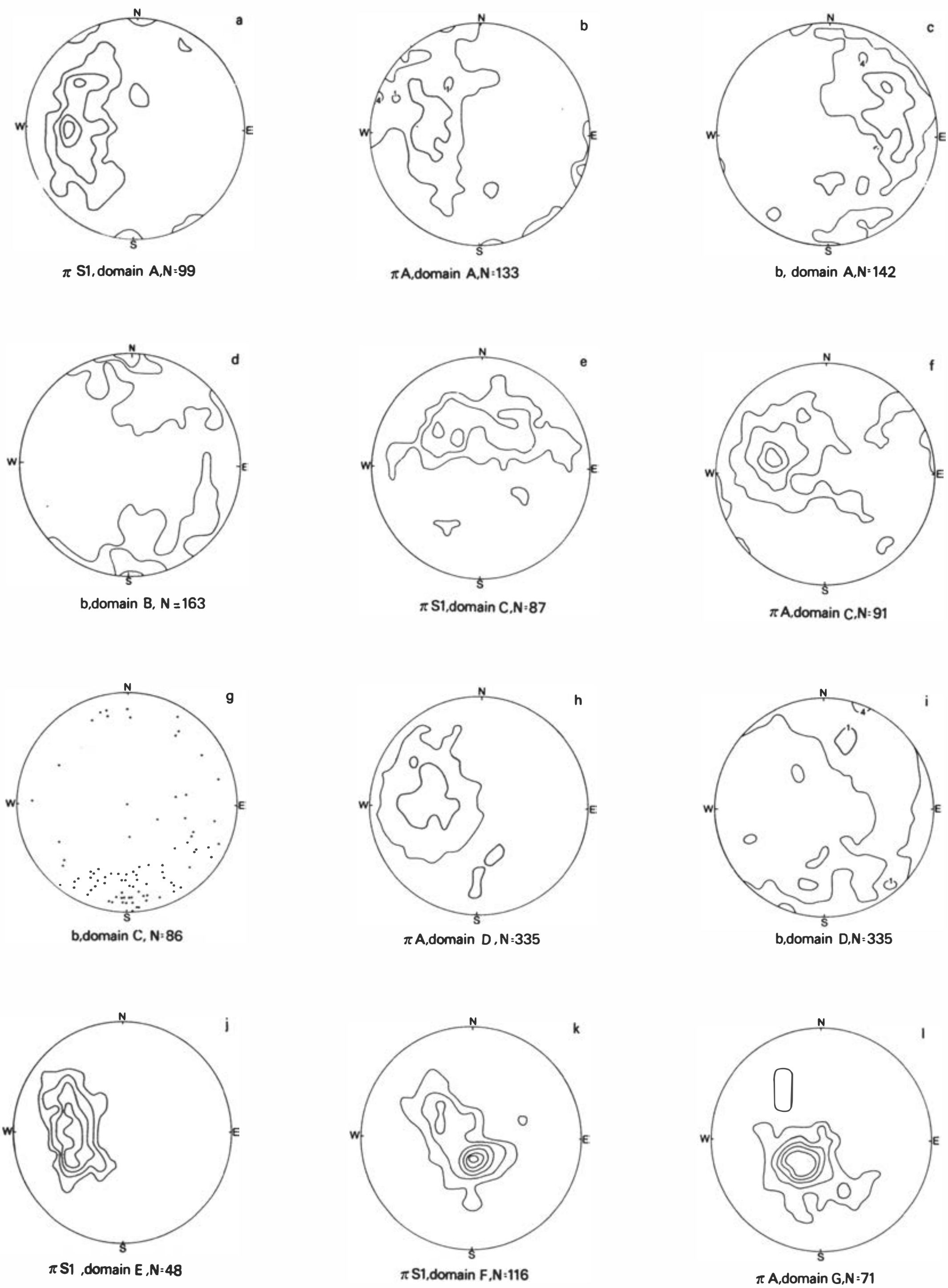


*Fig. 4.* Lower hemisphere, equal area projections of domains A to G. Contour lines 1, 4, 8, 12, 16 and 20 % per % area $\pi S_1$: poles to foliations; $\pi A$: poles to axial surfaces of minor folds; b: axes of minor folds.

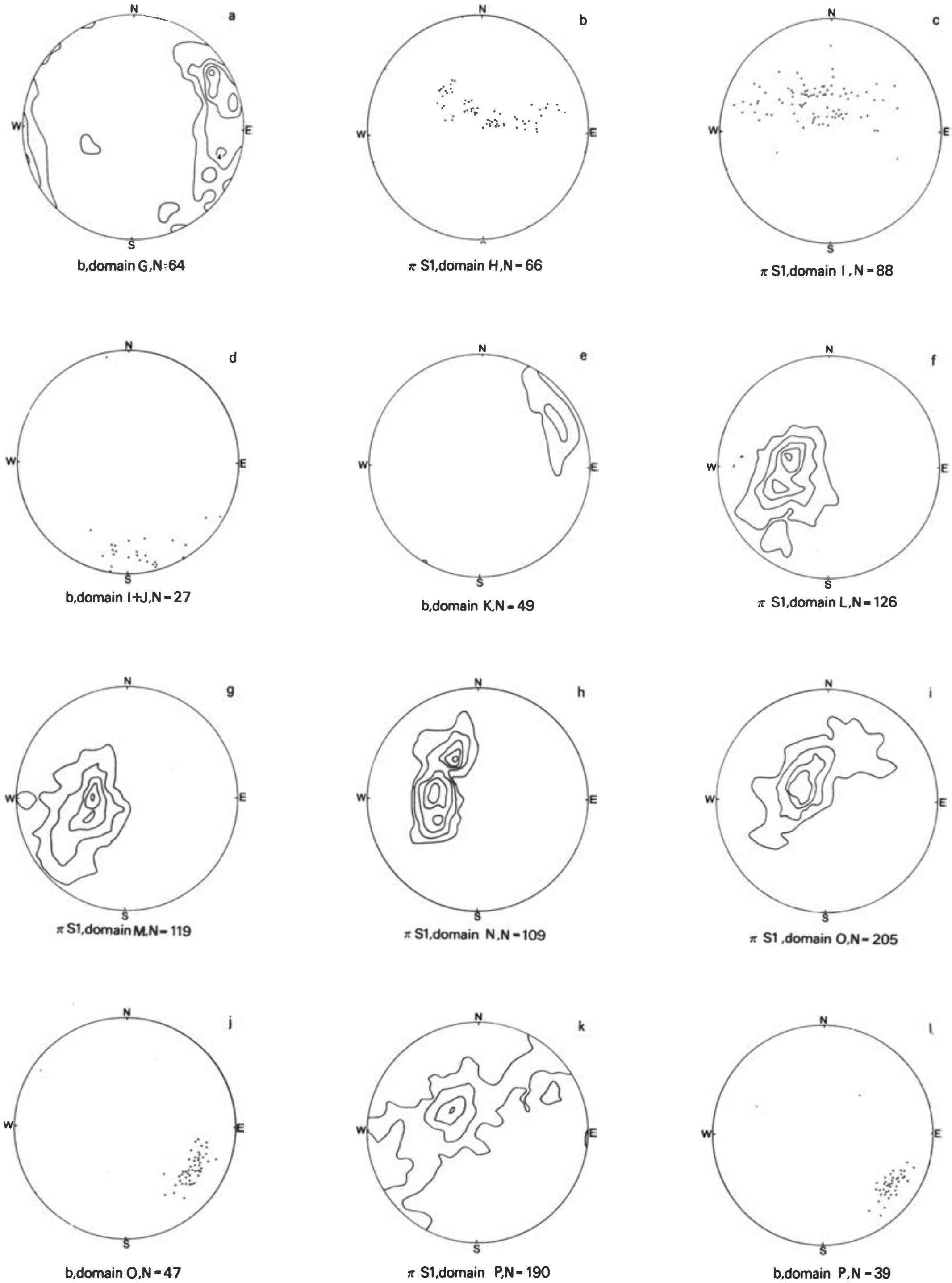


*Fig. 5.* Lower hemisphere, equal area projections of domains G to P. Contour lines 1, 4, 8, 12, 16 and 20% per % area. $\pi S_1$: poles to foliations; b: axes of minor folds.

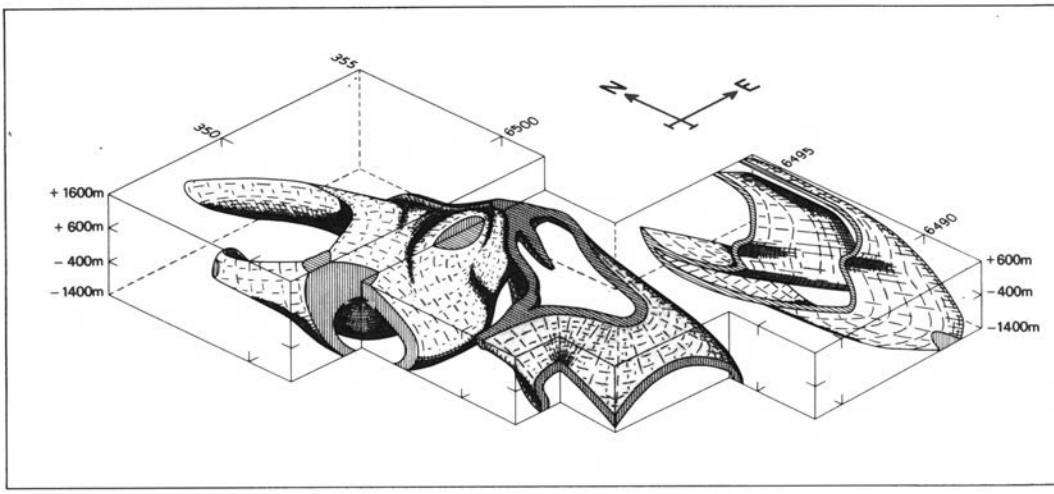


*Fig. 6.* Block diagram of the mapped area.

### *The southeastern part*

The outcrop pattern in the southeastern part of the area can be described as a large refolded isoclinal fold. Although on the scale of mapping a fold closure can be recognized east of Rusdalsvatnet, in the field the layering (defined by a distinct mineral foliation!) does not show any sign of folding (Figs. 2, 3). The fold axis of this isoclinal fold plunges probably ESE (Fig. 5-f). Refolding of this isoclinal structure has given rise to a reclined fold, whose axial surface dips ca. 30°E and whose fold axis plunges ca. 30°E (Fig. 5-g, h). A northward lobate extension of the garnetiferous migmatites, north of domain M, is solely due to topography.

A later deformation caused asymmetrical folds on the east limb of the reclined fold as can be seen on the map (Fig. 2). The axial surfaces of these folds dip ca. 45°NE. Fold axes plunge ca. 25°SE (Fig. 5-i, j).

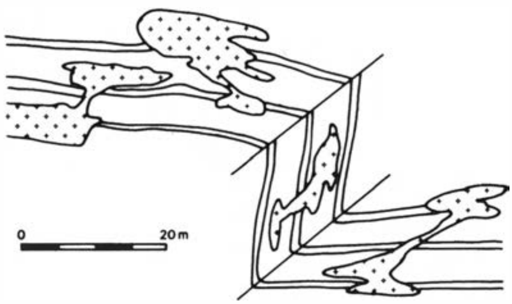


*Fig. 7.* Example of fold in charnockitic migmatites that are intruded by granitic rock. Drawing from photograph.

Minor folds are abundant and developed in a consequent style as a result of this refolding, even in the more massive surrounding charnockites (Fig. 5-k, l). The axial surfaces of these minor folds are often marked by shear zones, several centimetres wide, that are intruded by a coarse granitic rock. The same granitic rock is present as more or less concordant bodies which are connected by discordant veins (Fig. 7).

## Structural history of the area

The occurrence of refolded folds in the area indicates successive events of deformation. Overprinting relationships are obvious, especially in the northwestern and southeastern part. The following deformation phases which are mainly based on the macroscopic outcrop pattern, are tentatively suggested for the area:

$D_1$: An isoclinal folding, which resulted in a transpositional foliation. Relicts of these folds are found as intrafolial, isoclinal folds. The $D_1$-phase was coeval with high-grade metamorphism and probably migmatization (Hermans et al. 1975). The observations made on the fold closure of the isoclinal fold east of Rusdalvatnet suggest that this structure may be a $D_1$-fold as well.

$D_2$: Folding of the $D_1$ tectonic and metamorphic layering by a second deformation phase into very large, tight to isoclinal folds. This deformation phase was coeval with high-grade metamorphism with anatexis.
Examples of $D_2$-folds are the large isoclinal structure in the northwestern part of the area and the refolding of the large isoclinal structure in the southeastern part along the N striking axial surface. The original orientations of the $D_2$-folds in the area, determined by subtracting the effects of younger deformation phases, do not give a consistent pattern.

$D_3$: Refolding of the $D_2$-folds by a third phase into large, open to tight structures. Minor folds related to $D_3$ can often be easily recognized, e.g in domain C and O.
The second and third deformation phases together gave rise to the main structures of the area. Under high-grade metamorphic conditions, with anatexis, the layering of the migmatites was deformed in a plastic style, resulting in folds of varying styles and orientations. Although $D_3$- folds are more open than $D_2$-folds, a clear distinction is difficult. It is quite possible that both $D_2$- and $D_3$-folds belong to one extended deformation phase. The large $D_2$-folds, which were developed under ductile conditions, were refolded by $D_3$-folds under more rigid conditions, brought about by a decrease in temperature. $D_3$-parasitic folds were also developed.

$D_4$: The development of gentle to open folds with E-W-striking, steep axial surfaces and E-plunging fold axes. The $D_4$-folding is most obviously shown by zig-zagging of the N-trending layer east of domains F and G. The folds can be traced only for a few kilometres; their wavelength is 1 to 2 kilometres. No parasitic folds were developed.

# Discussion

The knowledge of the structural history of the high-grade metamorphic area of Rogaland/Vest-Agder is rather limited. For a general discussion the reader is referred to Michot (1960) and Falkum (1966, 1976).

Our conclusion that $D_1$ caused a transpositional foliation is supported by Falkum (1976, p. 92): 'The main foliation formed during the first phase of deformation ($F_1$) and underwent successive phases of refolding.' There is no disagreement about the youngest deformation phase. All authors recognize steep, E-W-trending axial surfaces. The wavelength of these folds is 1 to 2 kilometres. The deformation phases between $D_1$ and this youngest phase have defined the main structures of the area. Our interpretation of a long period of high-grade metamorphism coeval with intense deformation is in agreement with Falkum (1966, 1976). Where we recognize a $D_2$- and a $D_3$-phase, Falkum distinguishes three deformation phases ($F_2$, $F_3$ and $F_4$). The $F_2$- and $F_3$-folds are very difficult to distinguish from each other: 'The $F_2$- and $F_3$-phases are two phases of more or less the same style of deformation with a grade of metamorphism in granulite facies. It is therefore extremely difficult to separate the $F_2$- and $F_3$-structures unless one is refolded by the other' (Falkum 1976). The $F_2$- and $F_3$-folds can be correlated with our $D_2$-folds, the $F_4$-folds with our $D_3$-folds.

With regard to Michot (1960), it is difficult to make a correlation between the area he mapped, north of the Egersund anorthosites (Fig. 1), and our area. Michot proposes a $D_2$, whereby large thrust sheets are formed. His $D_2$ could be correlated with our $D_2$, although we did not find any evidence for such thrust sheets. It is clear that more detailed structural mapping is needed to elucidate the complicated tectonic history of the area of Rogaland/Vest-Agder.

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