Structural Interpretation of a Double-folded Gneiss-amphibolite Sequence, Bunnefjorden, Akershus

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Garnet amphibolite bands folded together with gneiss lamellae in tight to isoclinal folds are described. A structural analysis shows that the folds were formed during two separate deformation episodes. This conclusion has in particular a bearing on the problem of distinguishing between primary intrusive structures and simple and multiple fold-structures.

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Introduction

The structures under consideration occur in an area within the Precambrian basement of south-eastern Norway situated around the southern part of Bunnefjorden, 25 km south of Oslo (Fig. 1). Amphibolite facies paragneisses underlie most of the area; the dominant rock type is a rather heterogeneous granitic augen-gneiss. The megascopic structure is outlined by 100–200 m thick horizons of fine-grained two-mica gneisses (Fig. 1).

The bedrock of the area is often hidden by Quaternary deposits and only very seldom are there continuous exposures. It has therefore been of the utmost importance to the study of the mesoscopic structures, which are usually outlined by the numerous amphibolite horizons in the gneisses, that continuous exposures have been created during the enlargement of highway E 6, which crosses the area.

When amphibolite bands of intrusive origin are used in structural interpretation, one must distinguish between structures of primary origin and structures which have been generated during a later deformation. Further complications arise if the gneisses have been through several episodes of deformation, or if several generations of intrusive basic rocks occur. These problems will be treated in the following detailed analysis of a gneiss–amphibolite sequence exposed in a road-section along E 6. Some of the problems have already been briefly discussed by Graversen & Hageskov (1971).

Description of the road-section

Along the eastern side of E 6 several hundred metres of road-sections have been surveyed at the scale 1:100. The section which has turned out to be the most valuable is shown in Plate 1, and the location is given on the map in

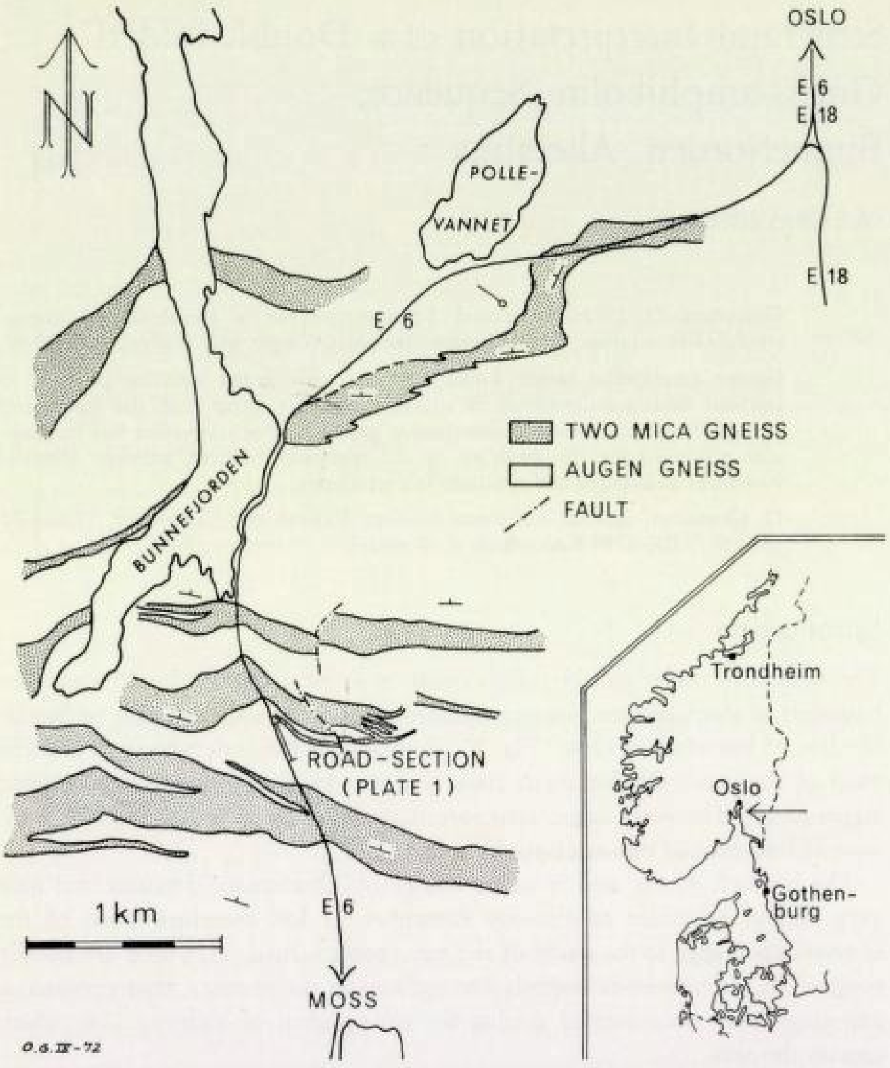

Fig. 1. Geological map (with inset location map) showing the position of the road-section shown in Plate 1. Compiled from field maps by O. Graversen, J. Thygesen and C. Zetterstrøm.

Fig. 1. The section surface is nearly vertical over long distances and the height varies from 10 m to about 25 m. The dominant rock type is the augen gneiss; in places it shows migmatitic veins, but in other areas the veins have been broken apart and augen are formed. The augen may have ellipsoidal form and a linear orientation, but it has not yet proved possible to carry out a meaningful strain analysis on the gneiss. However, the gneiss gives the impression of having undergone a very strong compression (Fig. 2). The general structure is indicated by concordant garnet amphibolite sheets of intrusive origin whose thickness varies from about 10 cm to 1 m. (The intrusive origin of the amphibolite has been demonstrated in gneisses from other parts of the area

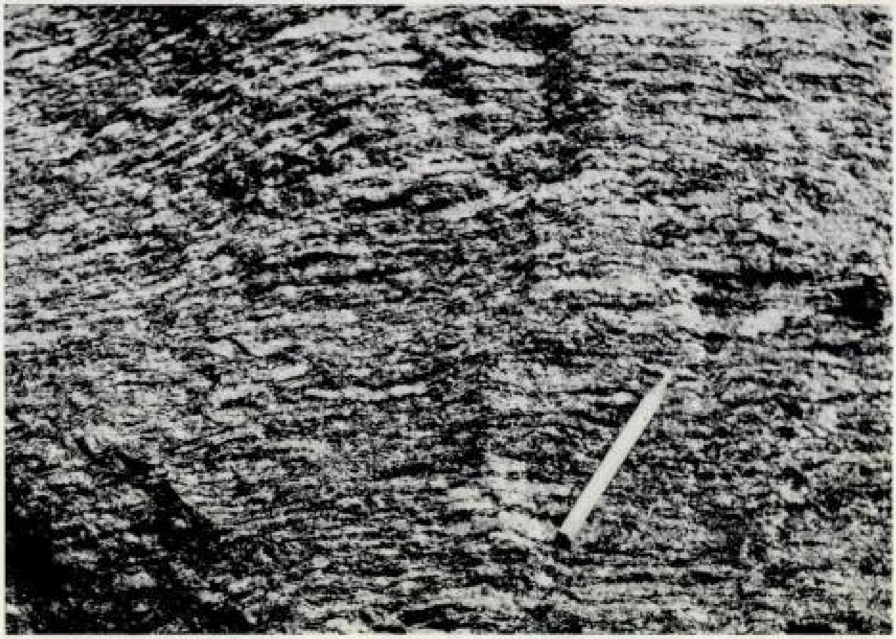

Fig. 2. Augen gneiss from the central part of the road-section shown in Plate 1.

which can be correlated with the rock sequence described in this paper.) This sequence is cut by discordant pegmatites deriving from the Bohuslän–Iddefjord granite, and by Permian dolerites. As can be seen from the section in Plate 1, the folded structure has not been disturbed by the cross-cutting dykes.

The garnet amphibolite sheets are folded in tight to isoclinal folds. At two places, central gneiss lamellae can be seen in amphibolite; both the amphibolite and the gneiss lamellae have been folded around a NW-plunging axis. One example of this is seen at the northernmost end of the section shown in Plate 1 and in Fig. 6, and the other is shown in the photo Fig. 3a, which was taken 110 m SSE of the section shown in Plate 1. One of the problems that will be treated in the analysis is whether these gneiss lamellae are remnants of screens in intrusive amphibolites, or whether they represent the cores of folds belonging to a fold episode older than the NW folding.

Much of the steep section is only accessible with difficulty, and it is not always possible to carry out accurate measurements. Where it has been possible to measure the fold axes, they always plunge to the NW, a direction that is also known from the regional mapping. Where observed, the NW axes always make a distinct angle with the section surface, because of the orientation of the road-section (N 20° W). On the flanks of the NW folds, the foliation is deformed around fold axes that trend almost parallel to the section surface – so, obviously, two axial directions are present.

Between the isoclinally folded amphibolites there occur amphibolite sheets which do not show a folded structure in the exposed part of the section, but nevertheless show concordant contacts against the gneiss (see for example

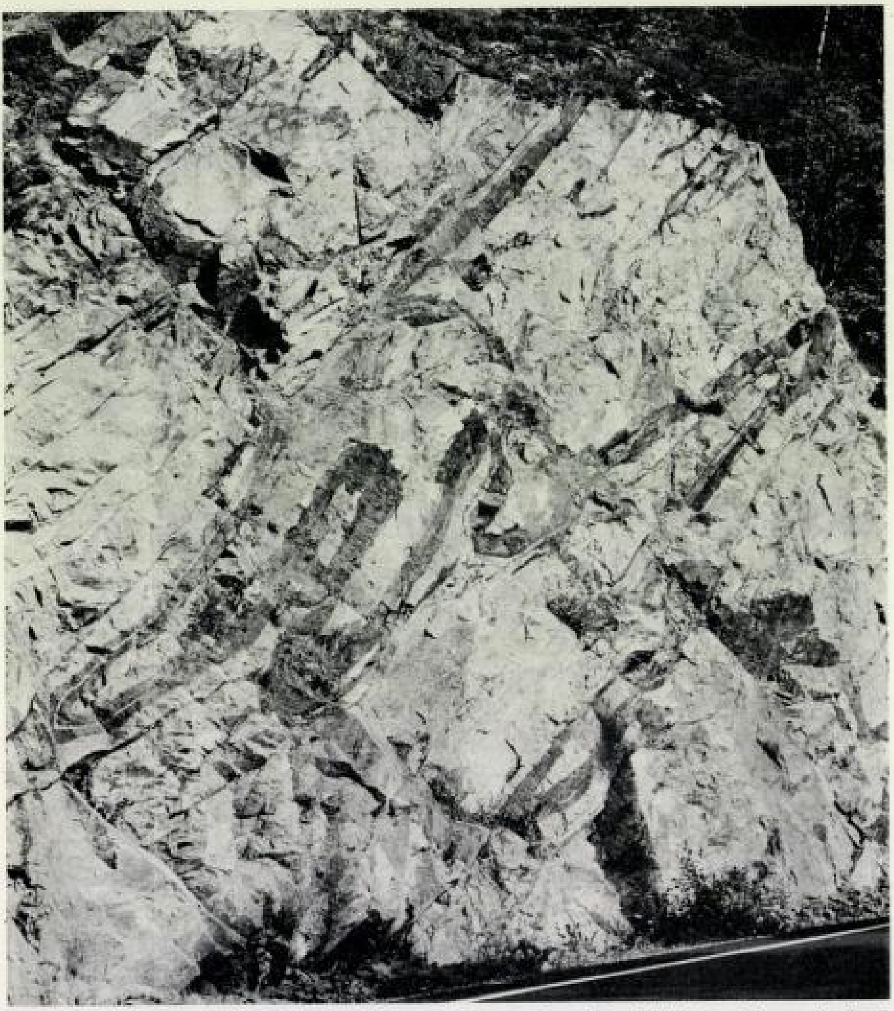

Fig. 3 a and b. Garnet amphibolite with central gneiss lamellae folded in tight to isoclinal NW plunging folds. (Photo along east side of E 6, 110 m SSE of the section in Plate 1).

Plate 1, 40–50 m, and in the southern part of the section). The question arises whether these seemingly unfolded amphibolites belong to the same generation as the remainder of the amphibolites, or whether they are sills belonging to an intrusive phase later than the NW folding. In order to clarify these and the questions mentioned above a more detailed structural analysis will now be given.

Structural analysis

During the analysis of the main structure the author used the 'paper and scissors method', which involves reproducing the structure in a model in which sheets of paper represent the marker layers, trimming these with scissors

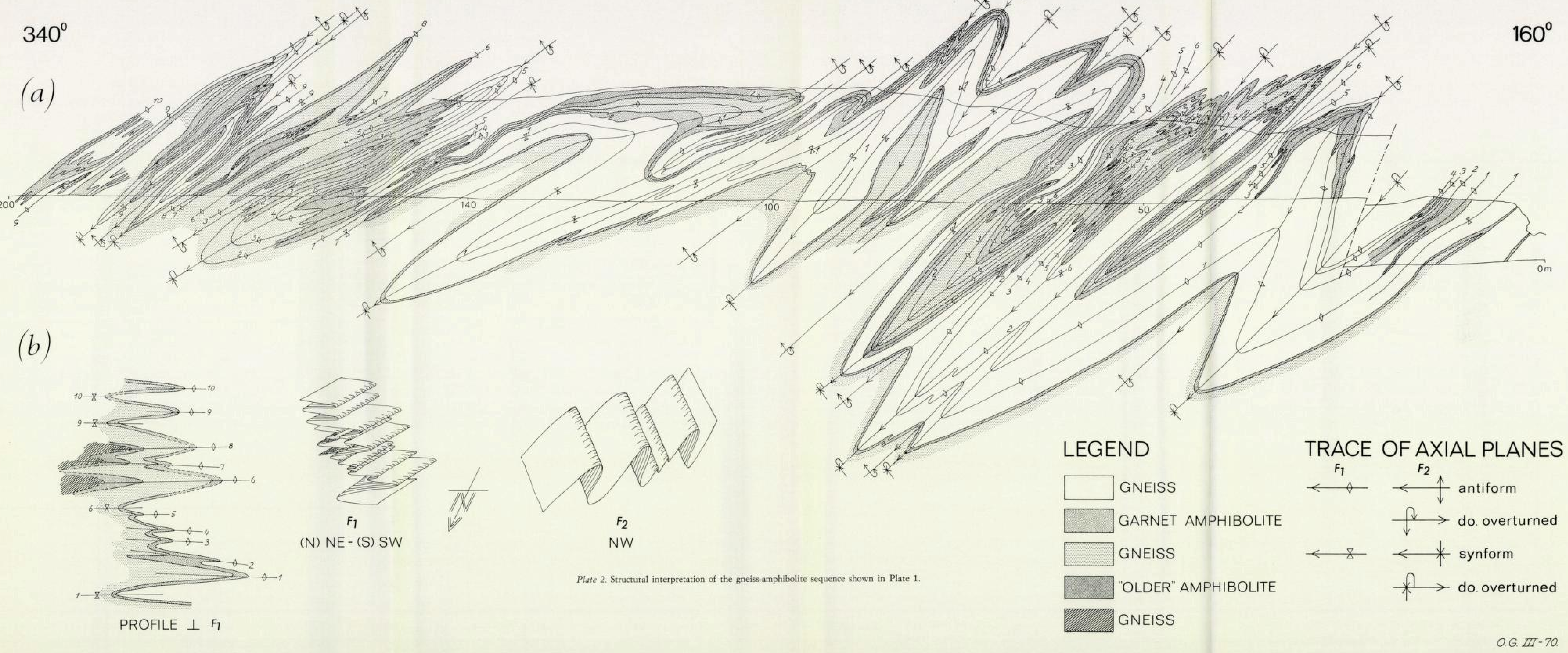

Plate 2. Structural interpretation of the gneiss-amphibolite sequence shown in Plate 1.

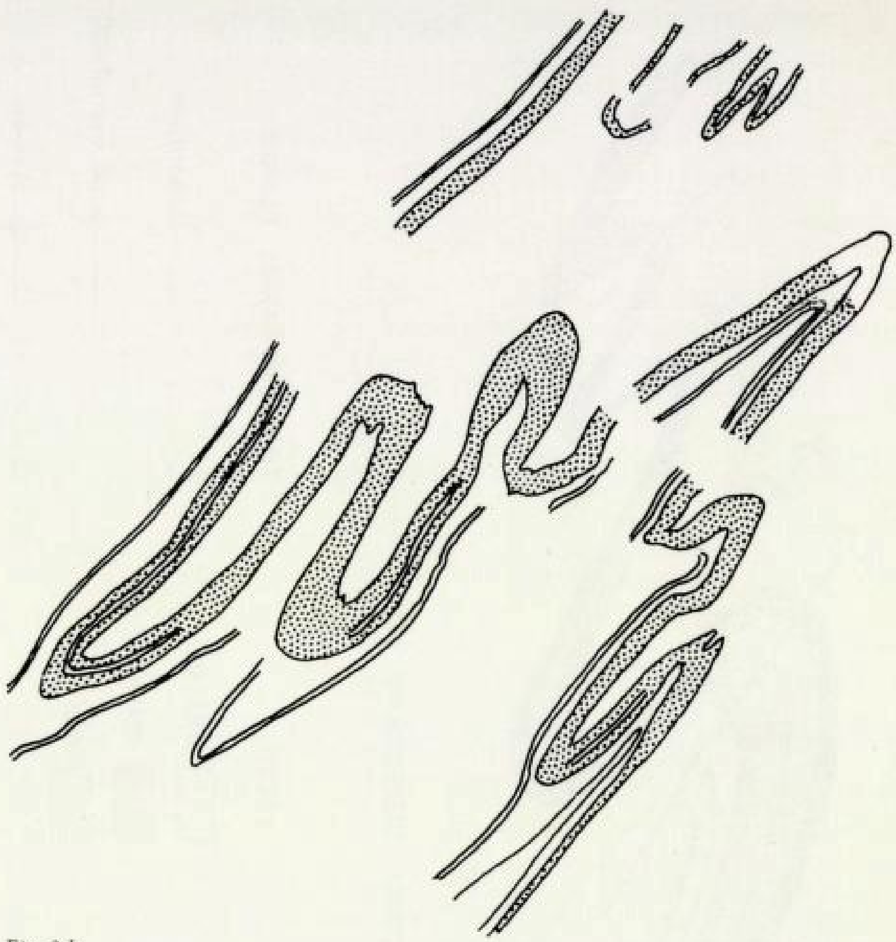

Fig. 3 b.

to produce the present erosion surface, and seeing if the model truly reproduces all the observed features.

The pattern shown in Fig. 4 is a partly schematic representation of the road-section between 90 and 150 m (see also Plates 1 & 2, and Graversen & Hageskov, 1971, Fig. 10), and it is now seen that gneiss forms not only lamellae but also larger cores in amphibolite. One also notices a distinct bilateral symmetry around the northernmost overturned, NW-plunging synform (X–Y); to the north the 'uppermost' garnet amphibolite horizon outlines two isoclinal folds, whose fold axes run subparallel to the surface of the section.

The bilateral symmetry and the occurrence of fold axes in diverging directions suggest the presence of more than one period of folding. The structure outlined in Fig. 4a may be explained as an interference pattern generated through the superimposition of NW folding on an older, tight or isoclinally folded, amphibolite sheet.

The older folding is now referred to as F_1 and the NW folding as F_2. The F_2 folding shows overturned tight to isoclinal folds that plunge to the NW at

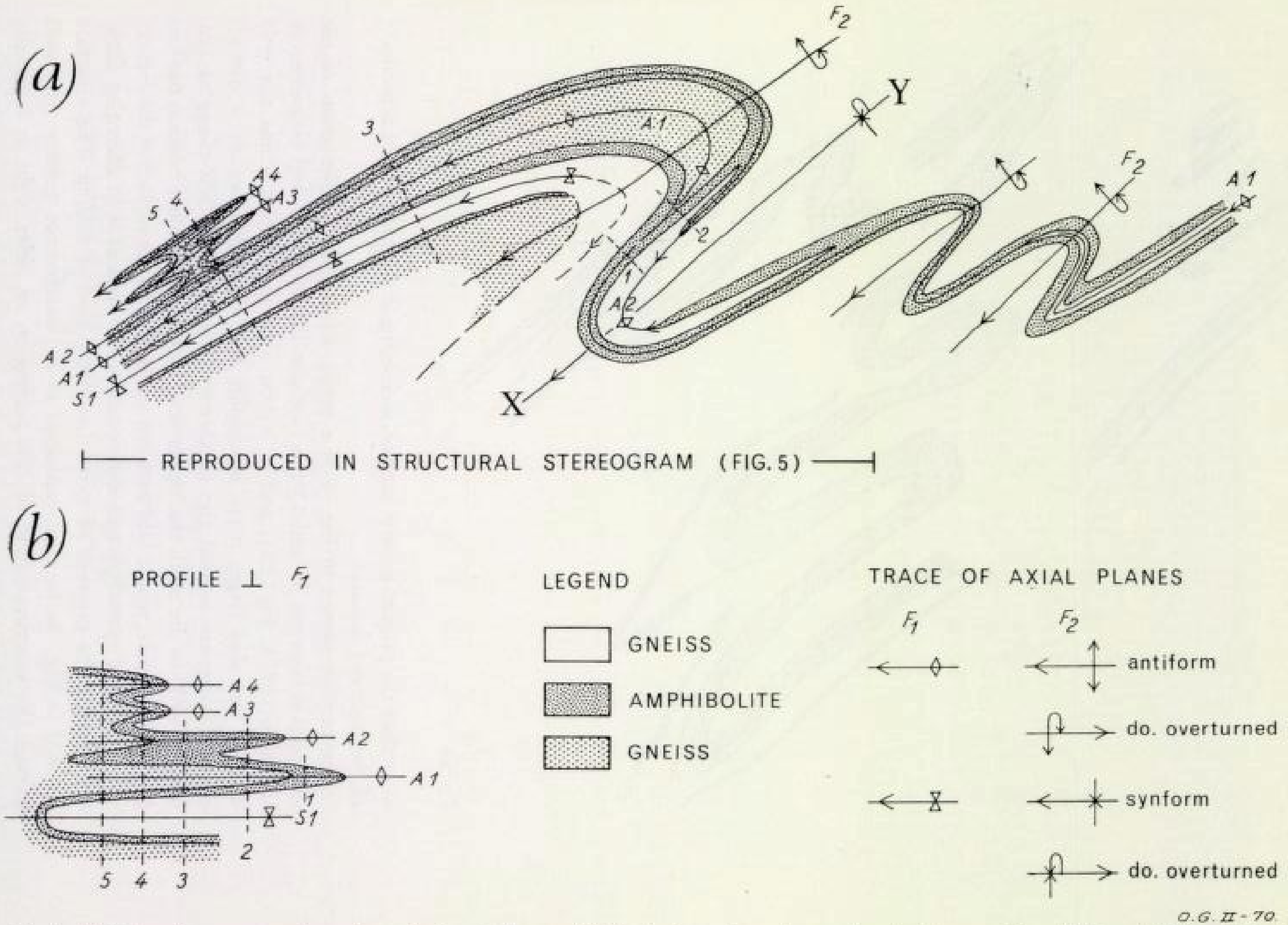

Fig. 4. (a) Schematic representation and correlation of the amphibolite horizons from the road-section between 90 and 150 m (cf. Plates 1 & 2). (b) Profile normal to the F_1 fold axis, looking south.

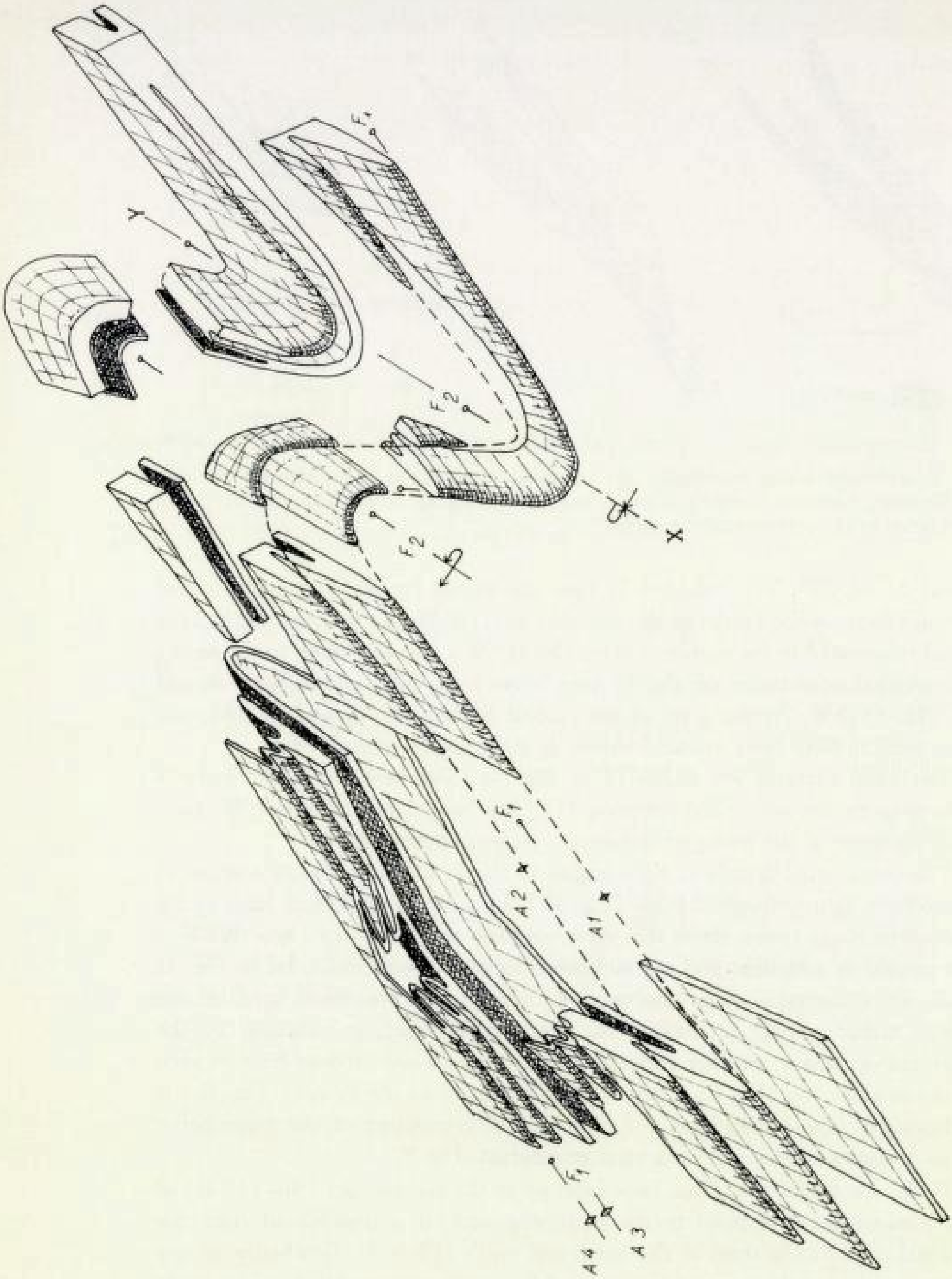

Fig. 5. Structural stereogram based on the structural analysis shown in Fig. 4.

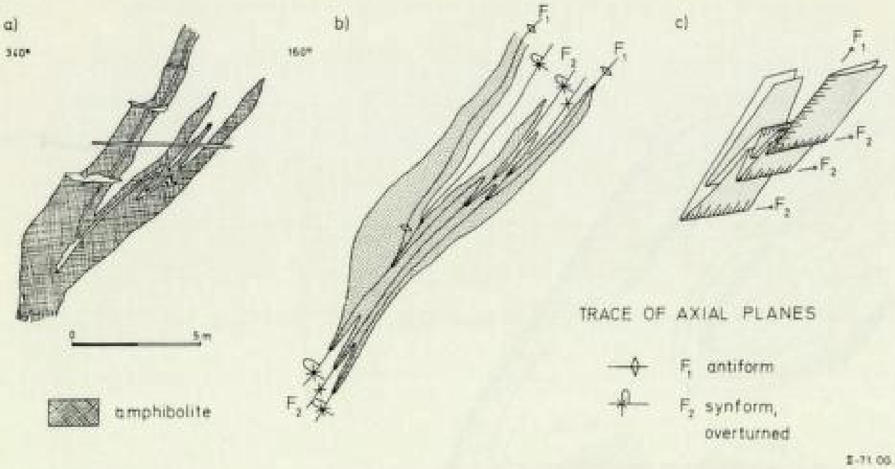

Fig. 6. (a) Double-folded amphibolite. (b) Structural interpretation of (a) showing the trace of the axial planes. (c) Tentative sketch where the orientations of the fold axes are shown in relation to the present road-cut surface.

about 5° to 25°. The refolded F_1 axes are shown by the isoclinally folded amphibolites on the flanks of the second ($=F_2$) folds. At present the F_1 axes trend subparallel to the section surface (N 20° W), but according to the model the original orientation of the F_1 axes must have been somewhere around (N)NE–(S)SW. At the start of the second folding the F_1 and F_2 fold axes thus seem to have been oriented almost at right angles to each other.

The axial surfaces are indicated in Fig. 4a, and here the axial surfaces belonging to the oldest deformation (F_1) are folded around the NW axes, whereas those of the youngest deformation are undeformed.

The constructed profile at right angles to the F_1 fold axis shows a series of recumbent tight to isoclinal folds (Fig. 4b). In order to be able to refer to the individual hinge zones, those that close towards the road – i.e., face WSW – are treated as anticlines and are numbered successively as indicated in Fig. 4; there are a corresponding number of synforms. The structural level of the gneiss, either 'above' or 'below' the amphibolite sheet, is indicated by the different ornament, and the correspondence between the erosion level as seen in the road-section (Fig. 4a) and the profile normal to the F_1 axis (Fig. 4b) is indicated by the dashed lines 1–5. The spatial orientation of the amphibolite sheet is represented in the structural stereogram, Fig. 5.

When the model which has been built up in the central part (90–150 m) of the road-section is applied to the remaining part, it is possible to trace the original amphibolite sheet to the north and south (Plate 2). Gradually, as one moves to the north, more of the original F_1 structure is revealed, and a more complete picture of this structure can be obtained. The gneiss from 155–175 m is structurally 'below' the amphibolite sheet folded during the first deformation, and this means that the garnet amphibolite lenses A 6–7–8, Plate 2, must lie at a 'lower' level compared to the rest of the amphibolites. These amphibolite lenses are therefore interpreted as the closures of folds in a new, separate amphibolite sheet (see profile perpendicular to the F_1 axis in Plate 2).

If the correlation between the northernmost amphibolite bands shown in Plate 2 is correct, all these bands (with the exception of those in the lenses mentioned above) belong to one and the same sheet, which is most probably the same sheet as that forming the more centrally situated amphibolite bands.

The northernmost structure in the road-section (Plate 1, 195 m, and Fig. 6) appears to fit well into the model built up so far, in which the centrally placed gneiss lamellae is a gneiss core formed during the first isoclinal folding, F_1, and refolded during the F_2 folding (Fig. 6b & c). The F_1 axis must trend parallel to the section surface, since the gneiss core has a constant thickness, and by unfolding the folds of the latest deformation the original orientation of the F_1 axis in the NE–SW quadrants is confirmed. That the structure is a refolded F_1 *anticline* (i.e., the amphibolite sheet closes towards the road) is seen from the fact that the gneiss core disappears in the southern limb whereas it continues throughout the northern one. (With the given axial directions, the reverse relations would appear in a refolded synclinal structure.) This structure is therefore naturally linked to the same sheet as the rest of the amphibolites, and does not reflect a primary intrusive feature of the amphibolite.

The structure outlined by the amphibolites in the southern part of the road-section (Plate 1, 0–90 m) can be explained as an interference pattern similar to those in the central and northern parts of the section, although only a part of the F_1 structure, S 1–A 6, is observed to the south (see Plate 2). This correlation also implies that only one generation of amphibolite is present.

It seems reasonable now to conclude that the structure pictured in Fig. 3 was also generated through two successive stages of folding. The central gneiss core disappears to the left, but fragments are seen at two other positions; this is due to the present orientation of the F_1 axis subparallel to the section surface. To the lower right the amphibolite sheet is quite thin (Fig. 3), and here the road-cut surface must be close to the outer part of the amphibolite fold closure formed during the F_1 folding.

Style and type of folding

The NW folding, F_2, generally shows a more open style than does the first folding, F_1 (Plate 2), wherein a considerable compression seems to have taken place, and this has led to a minor variation in the orientation of the F_1 axis.

Buckling is observed in the concave part of the hinge zones at several locations in the F_2 folds (see for example Fig. 3), and this together with the general style indicates that buckle folding played a major role in the second deformation. In contrast to this, a 'fork' can be observed in the hinge zone to the lower right in Fig. 3, and the formation of this is referred to a shear movement (F_2') parallel to the axial plane of the F_2 folds that occurred during or shortly after this folding.

Summary

From the detailed structural analysis of the gneiss-amphibolite sequence it has been possible to distinguish two periods of folding. It is only the presence of marker horizons that has permitted this interpretation; F_1 folds are impossible to observe in the strongly foliated gneiss alone, and even the second folds are often difficult to distinguish. On the other hand, when the amphibolite bands were used in the analysis, problems arose concerning the distinction between primary and secondary structures, together with the problem whether one or more generations of amphibolites were involved. These problems were solved through the structural analysis, which showed that the observed structures are not of intrusive origin, and that only one major sheet of amphibolite is present.

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Graversen, O. & Hageskov, B. 1971: Basic magma tectonics contrasted to folding of basic rocks. *Geol. Rdsch. 60*, 1442–1455.

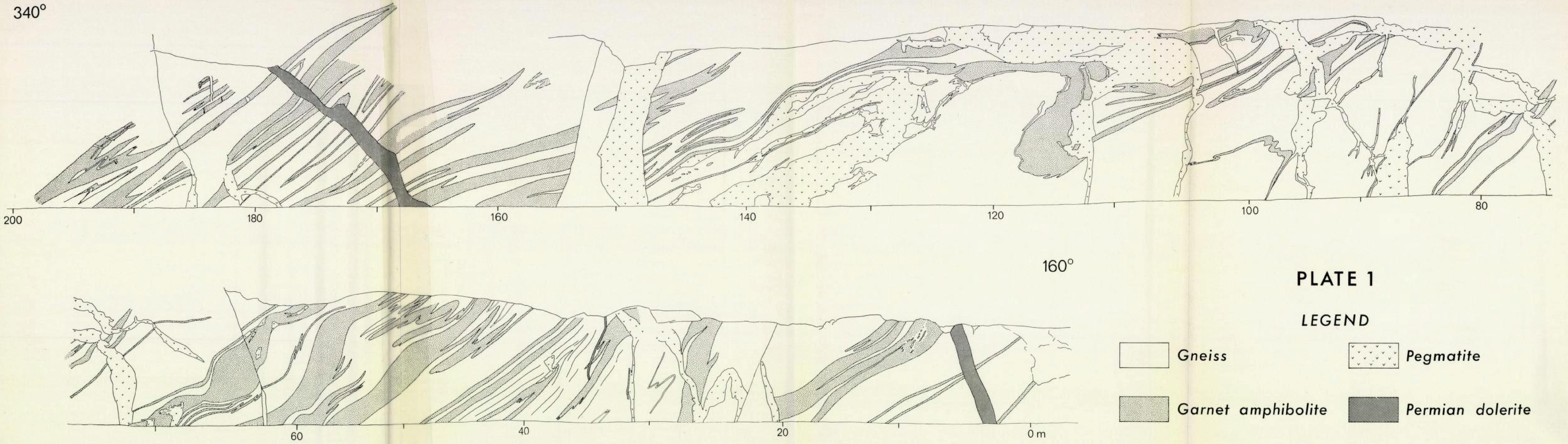

Plate 1. Outcrop-pattern of gneiss/amphibolite from road-section along the eastern side of E 6 (location is given in Fig. 1).

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