Caledonian Structural Geology and Tectonics of East Hinnøy, North Norway

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Rocks of east Hinnøy comprise three Caledonian tectonic elements: (1) parautochthonous pre-Caledonian crystalline basement (Lofoten block); (2) allochthonous Precambrian gneisses, probably derived from the Lofoten block, and metasedimentary rocks of the Storvann Group, which are interpreted to represent the Vendian/Cambrian(?) sedimentary cover of the Lofoten block; and (3) Caledonian cover allochthons (Narvik Group, Stangnes amphibolite and Evenes Group). The Lofoten block probably belonged to the Baltic craton in pre-Cambrian time, and is interpreted to lie presently at a lower structural level than the Caledonian allochthons.

Four Caledonian deformation phases are identified. D_1 and D_2 occurred prior to or synchronous with amphibolite-facies metamorphism, whereas D_3 and D_4 post-dated the metamorphic peak. D_1 emplaced the Caledonian allochthons upon the Lofoten block and at least some of its sedimentary cover (Storvann Group). During D_2, thrust sheets were detached from the upper surface of the Lofoten-block basement, imbricating and infolding these sheets together with the structural cover, which comprised both the Storvann Group and the D_1 cover allochthons. This resulted in further transport of the composite nappe stack relative in the Lofoten basement. Analysis of minor structures indicates ESE-directed transport during D_2. D_3 and D_4 formed upright to overturned folds which redeformed the tectonic stack, but probably caused no major tectonic displacements. Cross-folding during D_3 may reflect left-lateral transpression at a late stage of orogenesis, perhaps related to late- to post-orogenic left-lateral movements which have been inferred in other parts of the Appalachian-Caledonian orogen.

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Introduction

The Scandinavian Caledonides are one of the world's finest areas for studying behavior of the crust during continental collision. Formed by early to middle Palaeozoic collision of the Baltic and North American cratons, the Scandinavian Caledonide orogen is characterized by a stack of thrust nappes, containing primarily metamorphic rocks, emplaced in a southeastward direction upon Precambrian crystalline rocks and their discontinuously preserved autochthonous cover. Deep erosion has exposed the underlying crystalline rocks in three settings (Fig. 1): (1) the Baltic Shield, which is the foreland to the orogen; (2) windows through the nappe stack; (3) a discontinuous belt along the Norwegian coast located to the west of the nappe exposures (Western Gneiss Region). Exposures of Precambrian crystalline rocks to the west of a belt of nappes which include rocks of apparent oceanic origin (e.g. Gale & Roberts 1972, 1974) led Dewey (1969) to propose that the Western Gneiss Region was sutured to Scandinavia in the Caledonian orogeny. However, later study has shown that many of the nappes were derived from positions west of the modern Norwegian coastline, and passed over the Western Gneiss Region, which apparently belonged to the Scandinavian craton in pre-Caledonian time (Gale & Roberts 1974, Gee 1975, 1978)

The structural position of the Western Gneiss Region beneath the metamorphic nappes suggests that much of its intense metamorphism and deformation are of Caledonian age, generated at the deepest exposed levels within the orogen. This appears to be correct for the eclogite-facies metamorphism of the Western Gneiss Region in southwestern Norway (Griffin et al. 1981). However, Griffin et al. (1978) recognized only minor Caledonian metamorphism and deformation in the Lofoten Islands (Fig. 1); the structures and mineral assemblages there are largely Precambrian in age. This led them to hypothesize a shallow (3 to 9 km) structural level for the Lofoten block during Caledonian orogenesis (see also Brueckner 1971, Hakkinen 1977). This would exclude the possibility that it was buried by nappes which were at medium-pressure amphibolite facies conditions during or after their emplacement.

The boundary between the Lofoten block and

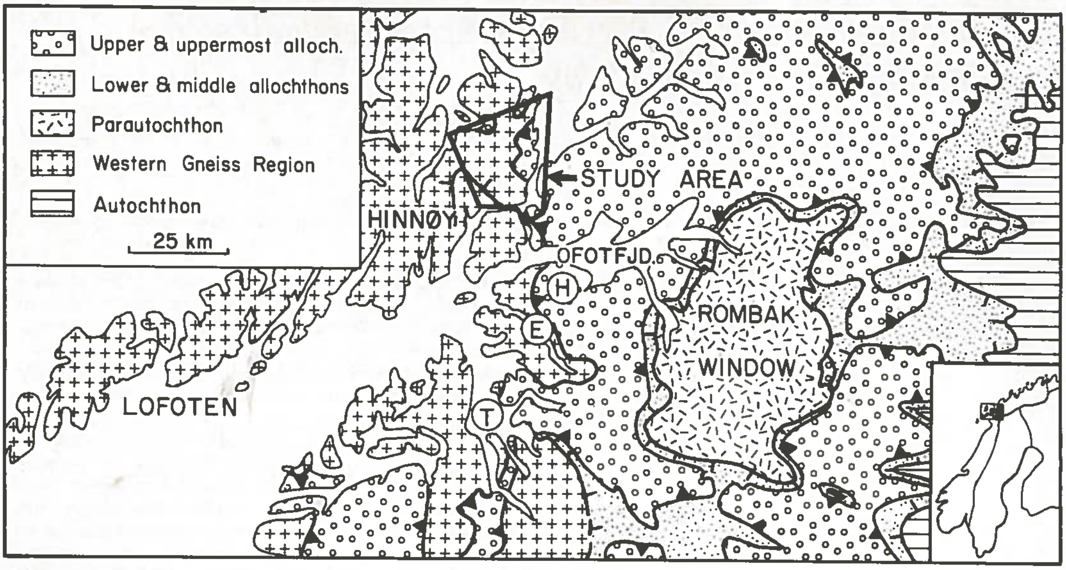

Fig. 1: Tectonic map of the Lofoten-Vesterålen-Ofoten area, modified from Roberts & Gee (1981b). H: Håfjell; E: Efjord; T: Tysfjord.

the Caledonian nappes lies on east Hinnøy (Fig. 1). This study examines this boundary and the structure of the rocks on either side of it, in order to attempt to (1) resolve the dilemma regarding the Caledonian structural position of the Lofoten block posed by the work of Griffin et al. (1978), (2) establish the extent and nature of involvement of the Lofoten block in Caledonian deformation on east Hinnøy, and (3) describe the structural and metamorphic history of the Caledonian nappes and their geometrical relationships on east Hinnøy to improve understanding of the conditions and kinematics of Caledonian deformation in this part of the mountain belt.

Previous Investigations

Heier (1960) showed that the rocks of Lofoten-Vesterålen are mainly intermediate to felsic igneous which experienced granulite-facies conditions of crystallization. This led to a major study by workers at the Norges Geologiske Undersøkelse (NGU) and the Geologisk Museum in Oslo, the results of which are summarized in Griffin et al. (1978) and Tveten (1978). A major conclusion is that the metamorphic and structural history recorded in Lofoten is almost entirely Precambrian; Caledonian effects appear to be few and minor (see also Tull 1977).

The Caledonian cover nappes, exposed to the east of Hinnøy, were studied by Vogt (1942, 1950) to the north of Ofotfjord, and by Foslie (1941, 1949) south of Ofotfjord. The metasedimentary rocks were considered to be Cambro-Silurian in age, and overlie the Tysfjord Granite, which appears to comprise retrograded equivalents of the granulite-facies rocks of Lofoten (Malm & Ormaasen 1978, Schubert & Bartley in prep.). The contact between the Lofoten block and the cover nappes is exposed on east Hinnøy. This contact was scarcely studied before the work of Gustafson (1966, 1972, 1974a, b), while preparing the Narvik 1:250,000 map-sheet (1974c). Gustavson (1972) interpreted quartzite and quartz-pebble conglomerate near Storvann (S) (see Plate 1 for location) to represent the parautochthonous cover of the Precambrian basement. Gustavson noted that the basement and the rocks that he identified as autochthonous cover had been deformed and metamorphosed in the Caledonian orogeny (1972, p. 37). Gustavson interpreted the relationships north of Storvann (S) (see Plate 1 for location) to represent imbrications of the basement and cover after emplacement of the cover allochthons. The present study represents significant revision of the map relations of east Hinnøy, but supports many of Gustavson's interpretations.

Tectonostratigraphy

Rock units of east Hinnøy can be divided into three assemblages: (1) pre-Caledonian basement rocks, which are considered to belong to the Lofoten block (Bartley 1981a); (2) the Storvann Group, a sequence of metasedimentary rocks interpreted to be in depositional or modified depositional contact with pre-Caledonian basement, and believed to be the Cambrian or Vendian sedimentary cover of the Lofoten block (Bartley 1981b); and (3) Caledonian cover allochthons, which include several distinct assemblages of metasedimentary and subordinate meta-igneous rocks (see below).

The lithostratigraphy of east Hinnøy is more complex than was previously reported. All metasedimentary rocks and most amphibolite bodies had been assigned a Cambro-Silurian age and assumed to be largely allochthonous along Caledonian thrusts (e.g., Gustavson 1972, 1974a, b, c). All of the metasedimentary rocks and amphibolite bodies west of Storvann (S) appear to be intruded by Precambrian granitoid bodies and hence are themselves part of the pre-Caledonian basement. In this study six different rock assemblages are included in the basement complex, three of which include metasedimentary rocks previously considered to be part of the Caledonian cover nappes.

Gustavson (1972) reported tectonostratigraphic sequence for cover rocks of east Hinnøy, but did not identify tectonic contacts within this cover sequence. The quartzite near Gausvik (Plate 1), which Gustavson considered to be autochthonous Eocambrian cover of the pre-Caledonian basement, appears to belong to the Hesjevatn assemblage, which is intruded by Svecofennian granite in the Hesjevatn area. This quartzite therefore belong to the basement rather than the cover, implying that the basement-cover contact is structurally higher in this area (see below). Here the cover is interpreted to include elements of at least four different stratigraphic sequences, the lowest of which, the Storvann Group, may be the stratigraphic cover of the Lofoten block.

Pre-Cambrian Basement

Basement rock associations of east Hinnøy include, from oldest to youngest: (1) *Archaean gneisses,* which include migmatitic gneiss (Griffin et al. 1978), a hornblende diorite body possibly related to the migmatites, and the Gullesfjord Granodiorite Gneiss of Hakkinen (1977); (2) the *Hesjevatn assemblage,* an association of amphibolite, quartzite, schists and marble; these rocks probably do not constitute a stratigraphic sequence, but are commonly assosiated rocks in pendants and blocks in the basement granitoid gneisses;.(3) the *Kvæfjord Group* (Bartley 1980), a sequence of quartzofeldspathic, micaceous, and mildly calcareous terrigenous metasedimentary rocks, which appear to be intruded by Precambrian granites (see below); (4) the *Middagstind Quartz Syenite* (Bartley 1981a), a middle Proterozoic (Svecofennian) pluton, similar in age and composition to the mangerites (pyroxenebearing intermediate intrusive rocks) which form the bulk of the Lofoten block; (5) the *Austerfjord Group* (Hakkinen 1977), composed of biotite-rich schist, calcareous para-amphibolite, and subordinate quartzite, psammitic schist and marble; and (6) the *Lødingen Granite,* dated by Griffin et al. (1978) at about 1400 Ma, which intrudes the Austerfjord Group (Hakkinen, 1977), and rocks related to the Svecofennian mangerite suite outside of the area of Plate 1. Age relationships between these units are not all well established, but it is reasonably certain that the Lødingen granite is the youngest.

On particular tectonic importance is the assignment to the basement of the Kvæfjord Group, the Hesjevatn assemblage, and the Austerfjord Group. Hakkinen (1977) established that the Austerfjord Group is intruded by the Precambrian Lødingen granite. An intrusive contact between the schists of the Kvæfjord Group and Precambrian granite is less clearly established, because these rocks are more strongly affected by Caledonian deformation. The irregular contact west of Storvann (N) (Plate 1) is a simplification of irregularities and complexities on the outcrop scale, which suggest that the granite injected the Kvæfjord Group schists. The schists commonly grade into migmatitic rocks adjacent to more homogeneous granite gneiss. In the core of the Kanebogen anticline (east of Harstad, Plate 1), paragneisses and schists are locally intermixed with granite gneiss on the outcrop scale. It is difficult to explain these relationships other than by igneous intrusion, but unequivocal intrusive contacts remain elusive.

An alternative interpretation of the Kvæfjord group is that it comprises a tectonic interleaving of Caledonian metasedimentary rocks and variably mylonitized basement granite, with tectonic contacts obscured by metamorphism (e.g., Gustavson 1972, 1974a, c). This possibility can be neither demonstrated nor excluded at present. Recent mapping near Tysfjord (Bartley & Schubert in prep.) indicates both similarities and differences between the Kvæfjord Group and some of the rocks imbricated with allochthonous Precambrian in that area. In particular, at Tysfjord we have seen no hornblende-bearing paragneisses which occur in the Kvæfjord Group on Hinnøy. More work is needed on the northern part of east Hinnøy to resolve this question.

Detailed mapping in the Middagstind area reveals that amphibolitic rocks there are part of the contact aureole of the 1726 Ma Middagstind Syenite pluton (Bartley 1981a). The broad outcrop area of the 'hornfels' reflects a nearly horizontal contact between the syenite and its wall rocks (Bartley 1981a, Fig. 2). Similar mafic bodies within basement granites occur in an arcuate belt that extends southeastward across the map area. Commonly associated with the mafic bodies are lenses of marble and quartzite, that also typically preserve static metamorphic textures (Bartley 1980). These rocks are referred to as the Hesjevatn assemblage. Granite dikes can be traced from the surrounding basement gneisses into the mafic bodies; two of these dikes yielded Precambrian Rb/Sr whole-rock model ages (Bartley 1980). In Hesjevatn area, these rocks, which were considered to represent klippen of the Lower Allochthon (broadly defined) (Gustavson 1972), also appear to belong to the Lofoten basement.

Southeast of Storvann (S), lenses of massive to foliated amphibolite, quartzite, marble and mica schist are interlayered with granite gneisses, some of which are blastomylonitic. The foliation in this zone is steeply dipping. These rocks lie along strike of less deformed but otherwise similar lithologies of the Hesjevatn assemblage located west of Storvann (S) (Plate 1). The Hesjevatn area also contains steeply dipping zones of blastomylonite, which appear to be a continuation of the blastomylonite zones of Storvann (S). These mylonite zones thus do not appear to follow the basement-cover contact (Plate 1), and therefore may post-date emplacement of the cover nappes. Gustavson (1972, 1974) considered these rocks in the area southeast of Storvann (S) to be allochthonous. This was based on the interpretation that the quartzite here assigned to the Hesjevatn assemblage is the autochthonous cover of the basement located to the south, therefore requiring that the mylonitized basement rocks to the north were emplaced upon the quartzite by Caledonian thrusting. Comparison along strike suggests to the present author that this quartzite belongs to the Hesjevatn assemblage, implying that the quartzite is intruded by, rather than deposited upon, the basement granite. Consequently, I interpret the Precambrian gneisses and metasedimentary inclusions southeast of Storvann (S) to be strongly Caledonized, parautochthonous basement, rather than far-travelled nappes. The basal thrust of the stack of cover allochthons is interpreted to occur substantially higher.

Caledonian Cover Rocks

The Caledonian cover rocks of east Hinnøy include elements of at least four distinct stratigraphic sequences. Stratigraphic subdivisions used in this study are: (1) the *Storvann Group,* a sequence of quartzite, schist and marble which is interpreted to be the Caledonian cover of the Lofoten block (Bartley 1981b); (2) the *Narvik Group,* represented by pelitic schists and gneisses with minor intrusions of granitoids and amphibolite, and present only in two tectonic lenses within a complex 'sliver zone' above the Storvann Group; (3) *Stangnes amphibolite,* a thrust-bounded slab of layered amphibolite intruded by a semi-concordant tonalite gneiss pluton; and (4) the *Evenes Group,* a sequence of metaconglomerate, marble and mica schist, which constitutes the highest unit of the nappe stack exposed on east Hinnøy.

All of the cover on Hinnøy was metamorphosed in the amphibolite facies during the Caledonian orogeny. The Storvann Group schists are generally more psammitic than pelitic, and commonly contain only the assemblage quartz + garnet + biotite + muscovite ± plagioclase ± hornblende. This indicates a minimum of garnet-grade metamorphism, but the absence of chlorite means this assemblage is consistent with metamorphism as high as sillimanite grade. Rocks which Bartley (1981b) assigned to the uppermost Storvann Group contain kyanite and locally fibrolitic sillimanite. Narvik Group pelites, on Hinnøy and elsewhere, commonly contain kyanite. Steltenpohl & Bartley (1984) found sparse but widespread occurrences of kyanite in the Evenes Group on the mainland immediately to the east of the area of Plate 1.

These relationships I interpret to indicate that the cover rocks may all be metamorphosed to kyanite grade. Steltenpohl (unpubl. data) has determined preliminary P–T values using microprobe data from pelites in the Evenes, Bogen and Niingen Groups on the mainland directly to the east of Hinnøy. The P–T values do not systematically vary from one sequence to another, and range from about 450°C and 5 kb to 650°C and 8 kb, which coincides with the trend reported by Hodges (1982b) for the Narvik Group. Retrograde metamorphism is common, but is patchy in its geographic distribution, and does not appear to be localized along either the basement-cover contacts or contacts between the cover sequences. No truncation or discontinuity of rock fabrics across these contacts has been observed. In combination, these data support the interpretation that the allochthons and the autochthon were juxtaposed prior to or synchronous with peak metamorphism. This carries the additional implication that the *basement* experienced Caledonian P–T conditions within the amphibolite facies without suffering extensive Caledonian deformation or metamorphic recrystallization, except in areas near the basement-cover contact (Bartley 1982a). Other evidence to support this interpretation is summarized in the discussion at the end of this paper.

STORVANN GROUP

Contact relationships, internal stratigraphy, and petrography of the Storvann Group have been described elsewhere (Bartley 1981b). This sequence, of apparent miogeoclinal or platformal affinity, probably reflects Vendian/Cambrian transgressive sedimentation upon the Baltic continental margin following late Precambrian rifting. An earlier paper interpreted the Storvann Group to be the autochthonous of the Lofoten block (Bartley 1981b). More recent mapping near Tysfjord (Fig. 1) shows that similar rocks there are allochthonous and intimately infolded and interleaved with transported Precambrian gneisses (Bartley & Schubert in prep.). The evidence for interpreting the Storvann Group as authochthonous (Bartley 1981b) supports a depositional contact between the Storvann Group and the immediately adjacent Precambrian gneisses, but does not exclude the possibility that those Precambrian rocks are transported. There are close mineralogical and geochemical similarities between the transported Precambrian gneisses in the Tysfjord area and retrograded mangerites of the Lofoten block (Foslie 1941, Gustavson 1966, Malm & Ormaasen 1978, Schubert & Bartley in prep.). This suggests that the transported basement was derived from the Lofoten block. Thus, the relationships are consistent with the view that the Storvann Group represents the Caledonian cover of the Lofoten block, but it has been transported southeastward from its site of deposition.

While the lower contact of the Storvann Group is concordant, the upper contact cuts across formational boundaries (Fig. 3; see also Bartley 1981b) and is interpreted to be a thrust fault.

Sliver zone

A complex mixture of lithologies forms a zone a few meters to perhaps 100 m thick, separating the Storvann Group from the overlying nappes. The lower contact of these rocks appears gradational with pelitic schist at the top of the Storvann Group, but probably represents a thrust fault. Penetrative deformation and metamorphism have apparently obscured relationships on the outcrop scale. Typically, this zone is an intimate mixture in varying proportions of four lithologies: (1) quartz-mica-plagioclase-calcite-epidote schists, (2) garnet-two-mica schists, (3) amphibolite, commonly garnetiferous, and (4) marbles, both calcite and dolomitic, commonly rather impure and grading into the other three lithologies. Lenses of Narvik Group lithologies occur within this zone (see below, and Plate 1). Boudinage is ubiquitous and often intense. The lithologic heterogeneity of this zone is interpreted as tectonic slivering along a major thrust. Other evidence for this thrust is presented later in the paper.

The term *Narvik Group* was used by Strand (1960) for a thick sequence of schists with subordinate marble and amphibolite in the vicinity of Narvik, about 60 km southeast of the study area. Gustavson (1966, 1974) correlated with the Narvik Group the sequence of schists, amphibolite, marble and ultramafic bodies which underlies the Evenes Group in Ofoten. Recent work indicates that the rocks thus grouped do not represent a single stratigraphic sequence (Hodges 1982a, Tull et all. in press). Some tectonic slivers on east Hinnøy include massive kyanite-bearing schists and gneises, cut by fine-grained granitic dikes, which closely resemble the structurally higher parts of the Narvik Group rocks near Efjord (see Fig. 1 for location). The term Narvik Group is here used advisedly, because a revision of nomenclature appears to be required.

Stangnes amphibolite

The Stangenes amphibolite occurs in the northeast corner of the study area as a thrustbounded slab, about 0.5 km thick, above the Storvann Group and one of the Narvik Group slivers, and beneath the Evenes Group. Evidence for the interpretation of the upper and lower contacts as thrust faults is presented later in this paper.

The Stangnes amphibolite is composed of fine-grained banded amphibolite which is intruded by the Ruggevik tonalite, a subconcordant sheet of tonalitic to trondhjemitic gneiss. The tonalitic composition alone suggests a rather primitive magma source. The initial $^{87}Sr/^{86}Sr$ ratio is less than 0.7045 (Bartley 1980), which supports this interpretation. It is unlikely that a tonalitic intrusion with primitive Sr was associated with early Precambrian continental crust at the time of its formation; similar plutons in other orogens (e.g., Kistler & Peterman 1973, Armstrong et al. 1977), are generally intruded into crust which was relatively young at the time of intrusion. Thus, it seems likely that the Stangnes amphibolite constitutes a far-travelled nappe. The Stangnes amphibolite may be related to the composite allochthon which comprises the Narvik Group, but this possibility cannot yet be evaluated.

The age of the Stangnes amphibolite is unknown. Rb/Sr whole-rock studies on the Ruggevik tonalite have not yielded an isochron. The entire complex underwent Caledonian metamorphism and penetrative deformation, for which Rb/Sr whole rock/biotite ages give a minimum age of about 360 MA (Bartley 1980). Sr whole-rock isotopic data suggest the tonalite is not likely to be older than about 1000 Ma (Bartley 1980). Because the wall-rocks of the tonalite were probably young when it formed, the approximate older age limit is considered to apply to the protoliths of the amphibolite as well.

Evenes Group

The Evenes Group is the highest unit of the nappe stack exposed on Hinnøy. These rocks are for the most part not well exposed and are structurally complex. No attempt was made to identify the internal stratigraphy or lithologic sequence on Hinnøy. Evenes Group rocks on east Hinnøy include: (1) the Harstad conglomerate (Gustavson 1972); (2) a series of variegated marbles, largely calcitic, including a distinctive pink to red-coloured marble; and (3) garnet-mica schist with minor calc-schist and garnet amphibolite.

The term Salangen Group was introduced by Gustavson (1966) to include the Evenes Group and overlying Bogen Group (Strand 1960), on the grounds that these rock sequences were not consistently distinguishable from one another. Recent mapping by Steltenpohl (in prep., Steltenpohl & Bartley (1984) supports a clear lithologic break between the Evenes and Bogen Groups in this area, and indicates that the contact between them is either a major unconformity or thrust fault. Thus, the distinction between these units is retained in the present study.

The Evenes Group lithologies of Hinnøy probably correlate with the Elvenes conglomerate, Ballangen marbles, and the basal mica schist of the Bogen Group of earlier workers (Foslie 1949, Gustavson 1966). Recent mapping by M. Steltenpohl (unpubl. data) on the mainland immediately east of Hinnøy places the contact between the Evenes and overlying Bogen Group within this upper schist. For the sake of simplicity, in this paper all of the upper sequence on Hinnøy is assigned to the Evenes Group, althoug a small amount of the Bogen Group could perhaps be present.

Gustavson (1972) considered the Elvenes conglomerate to be younger than the Ballangen marbles on the basis of marble clasts in the Harstad and Eveneskjær occurrences. However, the conglomerate at Eveneskjær appears to be a different conglomerate than that at Elvenes, occupying a position *within* the Ballangen marble sequence (M. Steltenpohl & J. Tull, in prep.). The marble clasts we have observed in conglomerate exposures at Harstad and Ballangen are not lithologically distinct from marble units within the Narvik Group. The Harstad conglomerate is here correlated with the Elvenes conglomerate, and I interpret this unit to represent the stratigraphic base of the Evenes Group.

The basal contact of the Evenes Group on Hinnøy is discordant, variously placing Harstad conglomerate, calcite marble or garnet-mica schist into contact with the Stangnes amphibo-

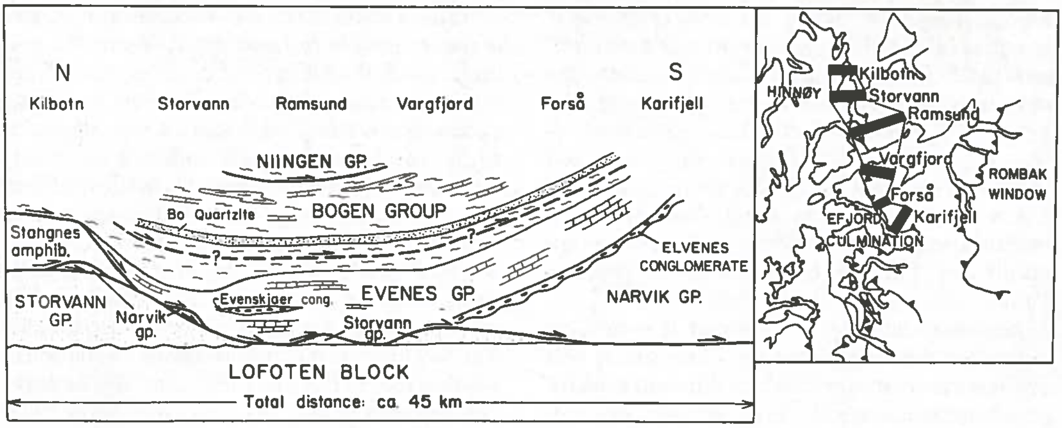

Fig. 2: Schematic relationship of the nappe stack at the end of Caledonian D_1, that is, before additional transport and refolding in D_2. Sources include the present study; Gustavson 1966, Hodges 1982, Steltenpohl 1983, and in prep., Tull et al. in press.

lite. This discordance suggests a tectonic contact, supported by the occurrence of mylonitic marble and calc-schist along the contact at the SE corner of the Stangnes peninsula. In the Håfjell region, the basal contact of the Evenes Group with the Narvik Group (s.l.) has been interpreted as an unconformity (Hodges 1982a, Tull et.al. in press). Probably, the unconformity exposed in the Håfjell area predates the emplacement of the allochthon containing the combined Narvik and Evenes Groups to its present position, so that on Hinnøy the unconformity is cut out by younger thrusting (Fig. 2).

Correlation of the Evenes Group with the Balsfjord Supergroup in Troms has been proposed (Binns 1978). The marbles of the Balsfjord Supergroup are less intensely metamorphosed (greenschist facies) and have recently yielded Late Ordovician to Early Silurian fossils (Binns & Matthews 1981, Bjørlykke & Olaussen 1981). This correlation conflicts with the interpretation of Hodges (1982a). Hodges considered the minimum age of metamorphism of the Evenes Group to be about 450 MA (i.e., late Ordovicoan) based on K/Ar hornblende ages from Narvik Group and basement rocks that he interprets to have been metamorphosed together with the Evenes Group. However, $^{40}Ar/^{39}Ar$ studies in the central and northern Scandinavian Caledonides have consistently revealed large amounts of excess Ar in hornblendes (Dallmeyer et al. 1983, J. Sutter & Bartley, unpubl. data); thus, Hodges's K/Ar ages must be interpreted with caution. Until better age data and more mapping are available, this conflict cannot be completely resolved.

Structural Geology

Structures of Precambrian, Caledonian and probable Mesozoic age are present on east Hinnøy. Precambrian structures are not understood in detail, partly because these were not the primary focus of this study, and partly because the relationships are not easily deciphered. Hakkinen (1977) indentified three phases of Precambrian folding on west Hinnøy in early Proterozoic supracrustal rocks. Presumably, at least the Archaean gneisses of east Hinnøy experienced the same periods of deformation. However, in these massive units it is impossible to separate the effects of the different Precambrian deformations. Where the Precambrian basement lithologies are more likely to record multiple deformations (e.g. the Kvæfjord Group metasedimentary rocks), the exposures are poor and the rock are strongly overprinted by Caledonian events. As a consequense, only general remarks are made about Precambrian structures.

Caledonian structures on east Hinnøy comprise a complex combination of thrust- and fold-nappe tectonics, overprinted by multiple refoldning. Four deformation phases, at least two involving thrusting, are recognized. Each phase prodused major structures and a characteristic suite of minor structures, summarized in Table 1.

As noted by Hakkinen (1977) and Griffin et al. (1978), Caledonian deformation in basement rocks is largely restricted to areas near the cover. Hakkinen (1977) considered this to be a function of structural level; he argued that the Lofoten block was a high-level nappe emplaced above the metamorphic nappe stack, so that metamorphic fabrics died out upwards as a result of reduced P-T conditions. This interpretation now appears to be untenable. Except locally, the Lofoten block lies at a structural level beneath the allochthons, as proposed by Gustavson (1972, also see Tull 1977). This downward disappearance of Caledonian effects has been attributed to limited availability of water to the granulite-facies Lofoten basement rocks (Bartley 1982).

An additional consequence of the variable and zonal deformation of the basement is that one deformation may produce different types of structures in basement and cover rocks, depending on structural position and previous structural history. For instance, thrust faults, steep ductile shear zones and recumbent folds all appear to have developed during the second deformation phase on east Hinnøy.

The results of this study lead to some differences in interpretation of the thrust-nappe geometry compared to that of Gustavson (1972). Gustavson's suggestion that the cover allochthons (assigned in his study to the Harstad Nappe) were emplaced first, followed by imbrication of the basement beneath, appears to be correct. However, the extent and geometry of the structures is different from that shown by Gustavson (1972, 1974a, b, c).

Several NE-trending Mesozoic(?) high-angle faults cut east Hinnøy into strips 2 to 5 km wide. Some of these faults were unrecognized previously, or were interpreted as Caledonian thrusts (e.g. the Langvann fault). Net slip is not known precisely for the high-angle faults. However, based on the lack of offset of steeply dipping rock units and fold hinge-surfaces, dip slip appears to dominate, commonly with downthrow on the northwest side (Bartley 1981c).

PRECAMBRIAN STRUCTURES

The preservation of Precambrian folds and fabrics is documented in the Middagstind area. The Middagstind Quartz Syenite is a discordant pluton, with no internal structural fabric except very locally, which cross-cuts foliations and contacts in the surrounding rock units. The Middagstind Quartz Syenite yielded a Rb/Sr whole rock age of 1726 ± 97 Ma (Bartley 1981a), and therefore the structures that it truncates must be at least early Proterozoic in age.

At least locally, a Precambrian foliation can be demonstrated in the basement. Within the contact zone on the east side of the Middagstind pluton, compositional banding is rarely preserved, and in thin-section, weak hornblende alignment within this banding locally defines a schistosity. East of the pluton, the hornfelds grades outward into rocks apparently unaffected by the contact metamorphism. It is unknown how the Caledonian foliations overprint the Precambrian schistosity here, but the two appear to be subparallel, perhaps explaining the subtlety of the transition. The foliation in the granite gneiss in the southwestern part of the study area may also be partly Precambrian in age (see also Gustavson 1972), but conclusive evidence is lacking.

A few Precambrian folds have been recognized. For example, it appears that the structural basin into which the Middagstind syenite intrudes is at least partly Precambrian. Foliations dip inward around the pluton, appearing to define a sharp-hinged E–W trending synform and a more open NW–SE synform (Plate 1). The latter structure is of Caledonian age (F_3). The former fold appears to be truncated by intrusions of the Middagstind syenite, which suggests a Precambrian age, post-dating formation of the Precambrian penetrative fabric discussed above.

CALEDONIAN STRUCTURES

The four Caledonian deformational phases on east Hinnøy (Table 1) can be split into two groups: pre- to synmetamorphic phases (D_1 and D_2) and late-metamorphic phases (D_3 and D_4). The early phases comprise the construction of the nappe stack, its emplacement upon Baltic basement and imbrication and infolding of the cover with the subjacent basement accompanied by further transport of the composite allochthon. Late-phase structures redeformed the nappe stack, complicating the picture but producing no major tectonic transport of the rocks in the study area. It is possible, even probable, that structures older than D_1 of this study have affected some of the rocks of the cover allochthons, but have not been recognized due to the intensity of D_1 and D_2 overprinting.

A significant break in time probably occurred between the synmetamorphic and late-metamorphic events. Most of porphyroblasts (kyanite, garnet, plagioclase, and hornblende in schists) grew either during D_2 deformation, or under static conditions after the synmetamorph-

Table 1: Sequence of Caledonian deformation phases on east Hinnøy.

Phase	*Faults and Shear Zones*	*Folds*	*Fabrics:*
D_1	Emplacement of allochthons along Stangnes and Tjeldsund thrusts.	None clearly distinguished.	Penetrative schistosity in cover, extends less than 1 km downward into basement. Mylonitic fabric near thrust contacts.
D_2	Austerfjord and Vikeland Thrusts. Steep ductile shear zones near Middagstind.	Recumbent folding, refolding D_1 thrusts, involving basement and cover together. A: up to 10 km O: variable V: ESE	Transposition and overprinting of S_1 to variable degree to produce new schistosity. Sparsely developed amphibole lineation. Boudinage.
D_3	Mylonitic shear zones in granite gneisses of basement.	Upright to overturned asymmetric folds A: up to 1 km O: WNW-ESE V: Mainly SSW	Spaced cleavage, intense in micaceous rocks, weak to absent in mica-less rocks.
D_4		Upright to overturned asymmetric folds. A: up to several hundred metres O: NE-SW V: variable	Spaced cleavage, similar to S_3.

A - Fold Amplitude; O - Fold axial orientation; V - Fold vergence

ic deformation, as shown by helicitic overgrowth of F_2 folds by the porphyroblasts (see below). There followed a period of cooling by as much as 200°C before the beginning of late deformations, based on retrograde mineral assemblages formed along S_3 and S_4 cleavage surfaces (Bartley 1980, Steltenpohl & Bartley 1984). However, D_1 and D_2 are probably parts of a continuum of early deformation, and D_3 and D_4 represent phases of a single period of late deformation.

NAPPE SEQUENCE

Figure 2 shows an interpretation of the vertical sequence of rocks on east Hinnøy at the close of D_1, and correlations with the nappe sequence further south. This interpretation is based upon the work of Hodges (1982a), Steltenpohl (1983, in prep.), and J. Tull (Tull et al. in press, and pers. commun.), as well as the present study. Gustavson (1972) recognized two nappes on east Hinnøy, the Harstad Nappe and the Straumsbotn Nappe. The Harstad Nappe included most of the rocks assigned here to the Storvann Group, the Narvik Group, the Stangnes amphibolite and the Evenes Group, plus a considerable amount of probable Precambrian rocks. The present study suggests that the Storvann Group and the Precambrian rocks with which it is infolded constitute a lower structural unit, distinct from the higher cover allochthons. This lower structural unit formed by detachment and transport of the upper part of the basement of the Lofoten block along with its stratigraphic and structural cover. Detachment of these basement thrust sheets occurred after emplacement of the overlying cover allochthons upon the Lofoten block, because thrusts and folds in this lower unit, assigned to D_2 here, deform the contacts of the higher cover nappes. The lower package may correlate with the imbricated basement and cover of the Middle Allochthon in Sweden, as suggested by Björklund (1981). However, the close affinities of the transported basement rocks for nearby slightly deformed parautochtonous rocks of the Lofoten basement suggests that this lower complex may not be as far-travelled as the Middle Allochthon.

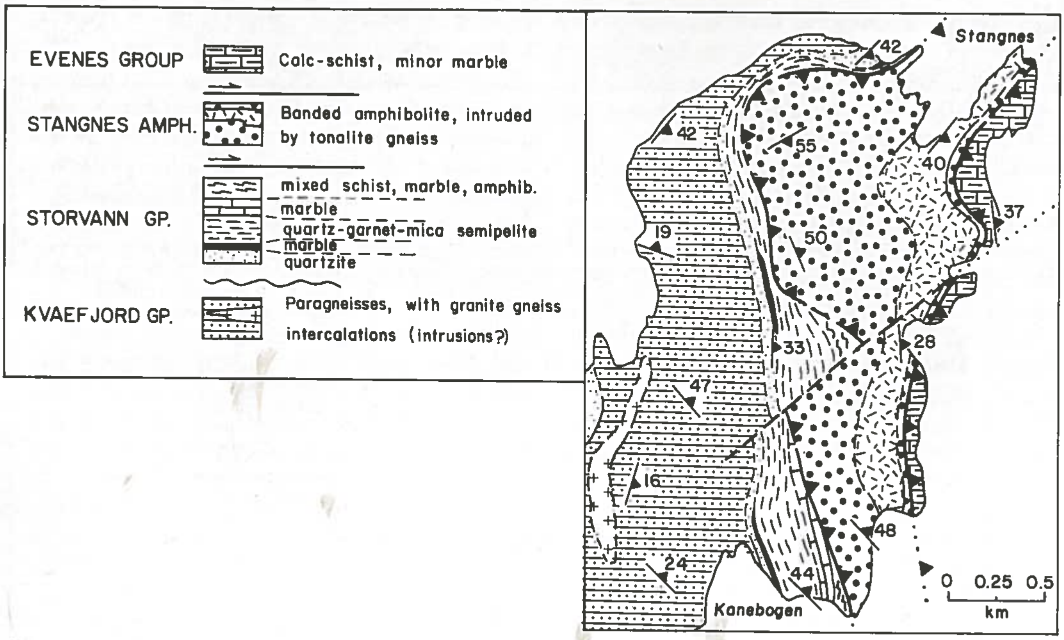

Fig. 3: Geologic map of the Stangnes area, illustrating truncation of Storvann Group rock units beneath the Stangnes amphibolite.

The relationships of the Harstad and Straumsbotn Nappes proposed by Gustavson (1972) are conceptually similar to the cover allochthons and the lower structural unit described here. However, the locations of contacts and structural style proposed by the present author differ from that of Gustavson (1972, 1974a, b, c). Cover units are not truncated beneath the transported basement; instead, a complete inverted tectonostratigraphic sequence is present, forming the upper limb of a tight to isoclinal fold (Plate 2, c–C'). Recent mapping of better-exposed but otherwise comparable infolded mylonitized basement and cover near Tysfjord (Bartley 1982b, Bartley & Schubert in prep.) indicates that the cover may be folded by draping around imbricate lenses of detached basement, which root into a shear zone at the top of relatively deformed basement. Thus, the style of the lower unit appears to be intermediate between imbricate slicing (Gustavson 1972) and recumbent folding (Bartley 1980).

D_1: Emplacement of Cover Nappes

Thrust faults. The name Stangnes Thrust is applied to the contact between the Stangnes amphibolite and the Storvann Group. It is well-exposed along shorelines at the north and south ends of the Stangnes peninsula. The thrust resurfaces to the west in the core of a major F_2 fold (Plate 1, Plate 2, C–C'), so that it is inverted in the intervening limb of the recumbent fold couple.

Several observations indicate this contact is a thrust. The contact is concordant at outcrop scale, but discordant on a regional scale (Fig. 3). At the southeast corner of the Stangnes peninsula, Stangnes amphibolite occurs above 200 m of Storvann Group rocks, including all five formations defined by Bartley (1918b), with an intervening zone of tectonic slivers. This contact cuts progessively down in the footwall as it is traced northwards, so that at the north end of the peninsula, several metres of quartzite, a lens of calcite marble, and a few metres of schist are all that is left between the amphibolite and the basement. This discordance suggests either an unconformity or a fault.

There are no Caledonian intrusions in the Storvann Group or Lofoten block, which weighs against an unconformable relationship. Furthermore, the amphibolite near the contact is commonly blastomylonitic, the mylonitic character of the fabric dying out over a distance of 50 m upward away from the contact. The lower contact of the Stangnes Group is thus interpre-

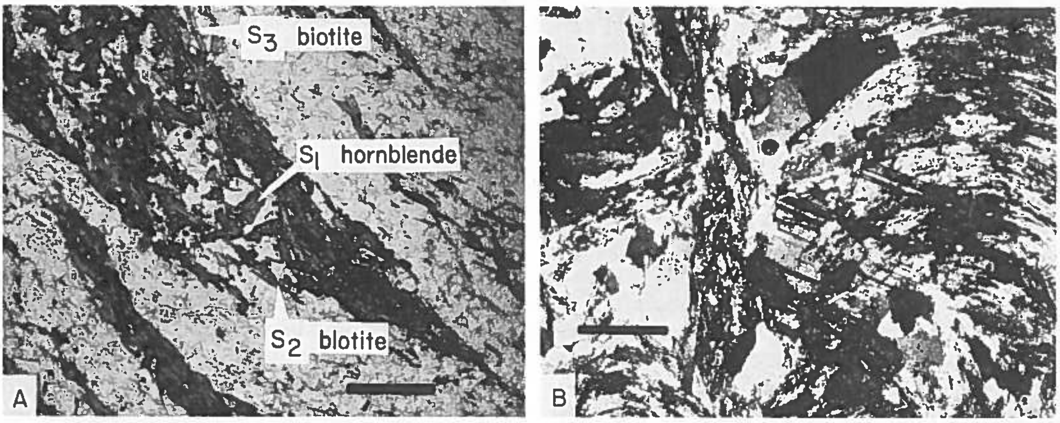

Fig. 4: Photomicrographs of textural relationships in polydeformed cover rocks.

a. Hornblende-biotite-bearing schist, Storvann Group, Finnslettheia. Axial-planar foliation (S_2) of isoclinal fold (F_2) is defined by biotite, while hornblende grains trace the folded S_1 foliation. Much of the biotite is recrystallized into S_3. Plane polarized light, scale bar = 2 mm.

b. Plagioclase–two mica graphitic schist, Storvann Group, Finnslettheia. Albite-twinned plagioclase porphyroblast (center) helicitically overgrows F_2 folds of S_1, replacing white mica but not displacing graphite. S_3 spaced cleavage surface (vertical, at left) truncates plagioclase porphyroblast. Crossed polars, scale bar = 0.5 mm.

ted to be a thrust fault, probably with large displacement.

In the blastomylonite amphibolite, the same minerals (blue-green hornblende, andesine, clinozoisite, sphene) have grown synkinematically in the penetrative schistosity that grew in the non-mylonitic schistosity of the rocks away from the thrust. There is no petrographic evidence for more than one schistosity in the amphibolite; the mylonitic fabric neither overprints nor is overprinted by the non-mylonitic schistosity. There is no angular discordance between the fabrics in the field. Thus, the penetrative schistosity, S_1, probably formed concurrently with emplacement of the allochthons.

The Stangnes Thrust probably formed early in the metamorphic peak. As summarized earlier, the existing data constraining the Caledonian metamorphic grade of the cover and basement in this area support uniform kyanite-grade metamorphism, although the evidence is not completely conclusive. No retrograde metemorphism is localized along the Stangnes Thrust. The rocks were still at high temperature when the thrust zone was folded during F_2, because D_2 deformation of basement and cover was accompanied by recrystallization of amphibolite-facies mineral assemblages; further, porphyroblasts minerals commonly helicitically overgrow S_2 (Fig. 4b). Consequently, movement on the thrust either predated or was synchronous with the peak metamorphism in the area, but the termal peak outlasted movement on the thrust.

No structures constraining the direction of emplacement of the cover allochthons were observed, partly due to the complex overprinting of this early deformation by subsequent events. Regional relationships require that the Stangnes amphibolite is westerly derived. Because the Lofoten block is not suitable basement for the amphibolite, a minimum distance of transport can be calculated assuming thrusting perpendicular to the modern limit of Lofoten basement some 60 km to the northwest. However, the Stangnes amphibolite probably travelled much farther than 60 km.

The name Tjeldsund Thrust is applied to the thrust at the base of the Evenes Group on the west side of Tjeldsund (Plate 1). Roadcut exposures at this location show a complex zone of interleaved marbles and schists, which places Evenes Group marble nearly in contact with Precambrian gneisses, with no more than a few tens of metres of Storvann Group rocks intervening. To the west, on the east shore of Storvann (S), a complete Storvann Group section occurs between the Evenes Group and the basement. Here, the sliver zone includes abundant calc-schists and garnet amphibolite scarcely present at Tjeldsund, with a lens of Narvik Group pelitic gneiss at the top. This discordance accompanied by tectonic mixing along the contact is, as with the Stangnes thrust, interpreted to indicate tectonic juxtaposition.

North of the Storvann Fault, the Evenes Group is separated from the Storvann Group by the Stangnes amphibolite. As noted earlier, contacts within the Evenes Group are truncated at its contact with the Stangnes amphibolite, which thus appears to be tectonic. This may be the continuation of the Tjeldsund Thrust. However, it is possible that the amount of movement on this contact is small and the Tjeldsund Thrust is equivalent to the Stangnes thrust north of the Storvann Fault. Field relationships allow either interpretation. A possible connection between the Stangnes amphibolite and the Evenes Group is the basal Elvenes conglomerate near Harstad and near Håfjell (Fig. 1), which appears to represent the base of the Evenes Group. The matrix of part of the Elvenes conglomerate is lithologically similar to the Stangnes amphibolite. However, no tonalitic intrusions are known from rocks unequivocally belonging to the Evenes Group, whereas the Ruggevik tonalite is ubiquitous in the Stangnes amphibolite on Hinnøy. It is conceivable that the amphibolite mathrix of the Elvenes conglomerate represents material derived by erosion of the Stangnes amphibolite, although it seems unlikely that such scarce lithologic change could occur in material of broadly mafic composition that had passed through a weathering cycle. This correlation problem awaits more data for its solution.

Fabrics. S_1 is a penetrative schistosity defined by dimensional and crystallographic preferred orientation of micas and amphibole, and to a lesser extent quartz and feldspar. Carbonate minerals have generally recrystallized to form equant grains defining a granoblastic texture. In micaceous rocks, S_1 is largely transported by S_2 except in hinges of F_2 folds. In non-micaceous lithologies, especially amphibolite, S_1 is generally folded in successive deformation phases with no new fabric development. No unequivocal F_1 folds were recognized; all early folds, minor or major, appear to fold the earliest schistosity and are assigned to F_2.

D_2: Interleaving of Basement with Cover and Transport of Composite Allochthon

Major Folds. Several large (amplitude $>$ 1 km) F_2 folds have been recognized in the study area. The general trend of the hinge-surface traces of these folds is NE–SW, except where re-oriented by later folds (Plate 1). When the effects of F_3 and F_4 folds are removed, the F_2 folds verge to the east or southeast (Plate 2), consistent with the transport direction determined below using minor structures. F_2 folds across the northern part of the area have been rotated by late folds, so that originally antiformal folds are now synformal, and synforms antiformal. The F_2 folds probably formed in a recumbent orientation. The hinges of post-F_2 folds are subhorizontal regardless of trend, which is only geometrically possible in the folded surface, in this case S_2, was nearly horizontal prior to folding. Thus, steep dips and plunges of F_2 folds are interpreted to reflect refolding.

In the discussion below, F_2 folds cored by Precambrian basement will be termed anticlines, and those cored by the cover nappes will be termed synclines. This conflicts with conventional usage of terms, but is broadly correct in that the anticlines defined this way do have the oldest rocks inside the closure.

Hinges of major F_2 folds are exposed only near Harstad and Finnslettheia. The hinge of the Harstad (antiformal) syncline can be walked out in essentially continuous outcrop. This fold clearly folds the nappe-emplacing thrusts and associated S_1 schistosity (Plate 2, c–C'). Hinges of other F_2 folds in the northern part of the study area are not exposed, but can be recognized on the basis of map relationships. For example, the Kanebogen (synformal) anticline is recognized on the basis of mirror-image sequences of Storvann Group and overlying allochthons across its hinge surface. Its synformal geometry is required by the presence of the Harstad antiform to the west, and is consistent with slight synformal convergence of dips on its limbs. This fold is important because it unequivocally demonstrates important basement involvement in F_2 recumbent folds. Both Kvæfjord Group rocks and granite gneiss occur in the core of this fold.

Major early fold hinges are also exposed on and near Finnslettheia (Plate 2, D–D'). On the east side of Finnslettheia, an eastward-closing syncline is present. To the northeast, another eastward fold closure is present, but this fold is an anticline (see also Bartley 1981b). An anticline and a syncline which close in the same direction require curving fold hinges, apparently a general characteristic of F_2 folds which is discussed further below.

The spatial relationships of the F_2 folds at Finnslettheia to those near Harstad is not obvious, but can be inferred by tracing rocks of the inverted limb between the Harstad anticline and Kanebogen syncline southward. The Storvann Group rocks traced from the southeast side of Storvann (N) south to the Langvann fault belong to the overturned limb of this F_2 fold couple (Plate 2, D–D'). Because the Langvann Fault dies out not far westward and thus cannot have large displacement, the inverted basement/Storvann Group contact north of the fault reasonably matches the same contact south of the fault on the top of Finnslettheia. This places the Precambrian granite on top of Finnslettheia in the core of the Kanebogen anticline (not synformal here). The F_2 folds on the side of Finnslettheia appear to be a second-order structures on the inverted limb, because in passing structurally downward to the east, no major reversal of the D_1 stacking sequence occurs (Plate 2, d–d').

The upper, upright limb of the Kanebogen anticline is only preserved in the Stangnes area and in one other place on east Hinnøy. Two kilometres to the east of the southern end of Straumsbotn, an F_3 synform is cored by Storvann Group quartzite and schist in upright sequence (Plate 1). Situated upon basement which cores the Kanebogen anticline near Finnslettheia, these rocks apparently belong to the upper limb of the Kanebogen anticline. Elsewhere on east Hinnøy, this upper limb has been removed by erosion, exposing lower elements of the D_2 structural stack.

The Evenes Group rocks on PLate 1 are interpreted to underlie the basement and Storvann Group rocks involved in the Kanebogen anticline. This is based on the actual observation of this relationship near Fjelldal, and the interpretation of the major F_3 folds east and south of Storvann (S) (Plate 2, D–D', E–E').

The amplitude of the major F_2 folds is large but poorly constrained. Simple measurement of the present minimum distance between adjacent anticlinal and synclinal hinges, using the basement/cover contact as a datum, yields amplitudes of 5 to 10 km. These are probably reasonable minimum estimates. Although F_2 structures were strongly refolded in later deformational events, the axial trend of F_2 folds, probably near the intermediate strain axis for D_3, is nearly perpendicular to the F_2 hinge-lines. Consequently, the post-F_2 length change in a NW–SE direction across most of the area (excluding areas of strong F_4 folding) was probably not large after F_2 folding.

A long-known problem of the Scandinavian Caledonides is that early fold axes are commonly oriented transversely to the trend of the mountain belt (Kvale 1953). This has stimulated considerable discussion, and a variety of mechanisms have been proposed to explain this fold

Fig. 5: Eye-fold in Storvann Group quartzite, east shore of Storvann (S), interpreted to have formed as a sheath fold. Lens cap (5 cm diameter) at right-center gives scale.

orientation, including (1) initiation of fold axes at low angles to the transport direction (Hansen 1971), (2) progressive rotation of fold hinges into the transport direction by continued strain (Bryant & Reed 1969), and (3) tectonic transport parallel to the trend of the orogen (Olesen 1971). On east Hinnøy, the major early (F_2) fold axes are oriented mainly parallel to the trend of the mountain belt. This tends to support Hakkinen's (1977) preferred interpretation of the transverse early fold axes in the Austerfjord area (formed during Hakkinen's F_1, which correlates with the present F_2; see discussion of Austerfjord Thrust below). Hakkinen believed the transverse early folds in the Austerfjord area of Hinnøy were produced by rotation of early folds by continued strain, which rotated the fold axes toward the shear direction.

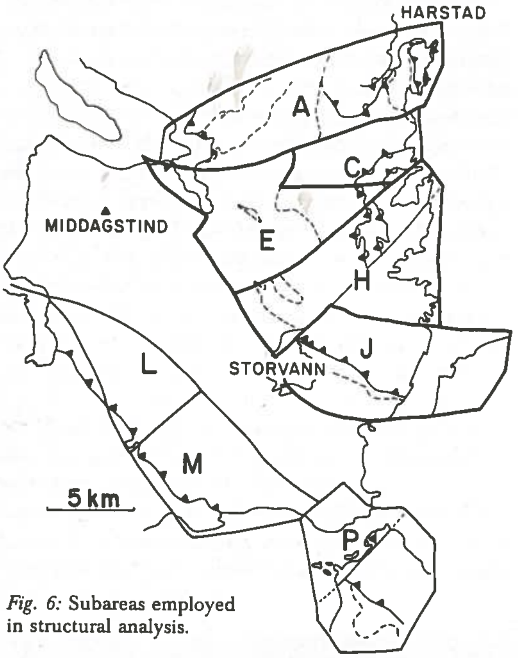

Fig. 6: Subareas employed in structural analysis.

Minor Folds. Minor folds of F_2 age are common in the metasedimentary rocks of east Hinnøy. They are tight to isoclinal and fall in style classes 1C and 3 (Ramsay 1967). Amplitude to wavelength ratios vary from about 3 to greater than 10. Fold hinges are commonly completely isolated by attenuation. In some areas, eye folds are observed on outcrop scale (Fig. 5). Most of these folds correspond to F_1 of Gustavson (1972). They are here assigned to F_2 because careful examination shows that these folds deform the earlier foliation (Fig. 4a).

Although good three-dimensional exposures of F_2 fold hinges with determinable asymmetry are not common, those F_2 hinges measured are plotted in Fig. 7, grouped into subareas as shown in Fig. 6. A wide variety of orientations are represented, but the folds verge consistently to the south and east. The variability of axial trends allows determination of a separation angle (Hansen 1971), the angle between domains of opposite fold vergence on a stereographic plot.

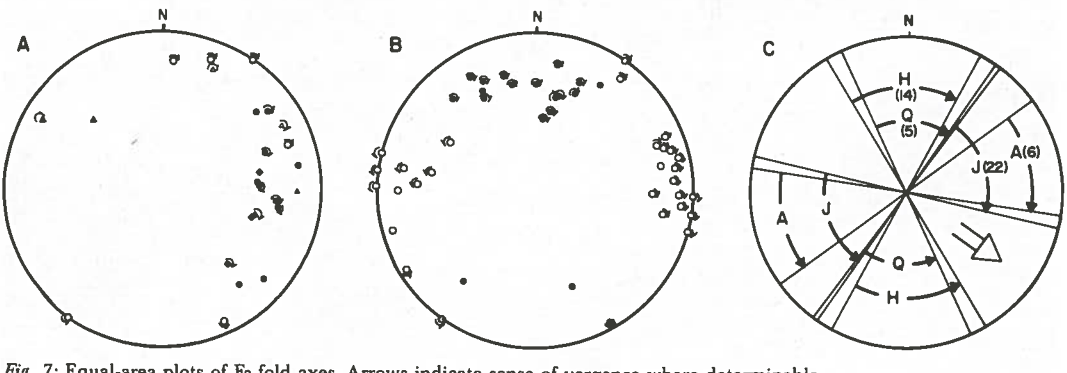

Fig. 7: Equal-area plots of F_2 fold axes. Arrows indicate sense of vergence where determinable.
a. Subareas A (filled circles), E (filled triangles), L (filled squares), M (open triangles), and P (open circles).
b. Subareas H (filled circles) and J (open circles).
c. Comparison of separation angles determined for subareas with more than two F_2 axes with determinable vergence. F_3 effects were removed by removing plunge of local F_3 fold axis, then rotating F_2 axis to horizontal around F_3 axis. Sectors bounded by radial lines contain all F_2 axes measured in a particular subarea; arrows indicate fold vergence within the sector. Numbers in parentheses indicate the number of fold axes used. Open arrow indicate shear direction which could have produced the observed relationships.

As noted earlier, the low plunge of post -F_2 folds, regardless of trend, requires that the F_2 folds were at least approximately recumbent, and therefore F_2 hinges were subhorizontal. Most of the effects of post-F_2 folds can thus be removed by rotating F_2 hinges to horizontal around the local F_3 or F_4 axis (Fig. 7). This defines a sector on the ESE side of the plot, which is the separation angle for the F_2 folds.

The spread in F_2 axes could be interpreted in at least four ways: (1) areally variable slip between planar volume elements could cause strain trajectories to vary, producing a variety of fold-axial orientations (the tundra-slide model of Hansen 1971); (2) the surface folded may not have been strictly planar, or the superposed strain field not spatially homoaxial, leading to a variety of orientations of intersections between the folded surface and the shear plane of the folds (Ramsay 1967, p. 540–5); (3) continued simple-shear strain during folding could rotate fold hinges, initiated at high angles to the maximum elongation direction, toward the maximum elongation, yielding a variety of orientations ('sheath fold' mechanism; Bryant & Reed 1969, Carreras et al. 1977, Bell 1978); or (4) a constrictive strain field may produce curving fold hinges as a consequence of shortening in the fold axial direction (Borrodaile 1972, Ramsay & Sturt 1973, Treagus & Treagus 1981).

Mechanisms (1) and (2) apply for passive folds produced by heterogeneous simple shear along the fold axial plane, while (4) relates to folding due to buckling instability. Mechanism (3) may reflect either fold mechanism. The passive shear-fold mechanism has been challenged on mechanical grounds (see Johnson 1977, Ch. 1, for a review), and appears to conflict with the observation that axial-plane foliation typically forms parallel to the XY-plane of finite strain, i.e., the fold axial-plane is a surface of little or no shear strain (e.g., Siddans 1972). Consequently, the author prefers mechanisms (3) or (4), between which the difference is whether the fold axes are curved by buckling or shearing. In either case, probably the appropriate kinematic interpretation of the separation angle is that it contains the maximum bulk finite elongation of F_2. The D_2 deformation comprises overturned folds and ductile thrusts of consistent SE vergence, consistent with development in a large-scale south-east-directed simple-shear couple. The elongation direction is interpreted to be the direction of tectonic shear during D_2.

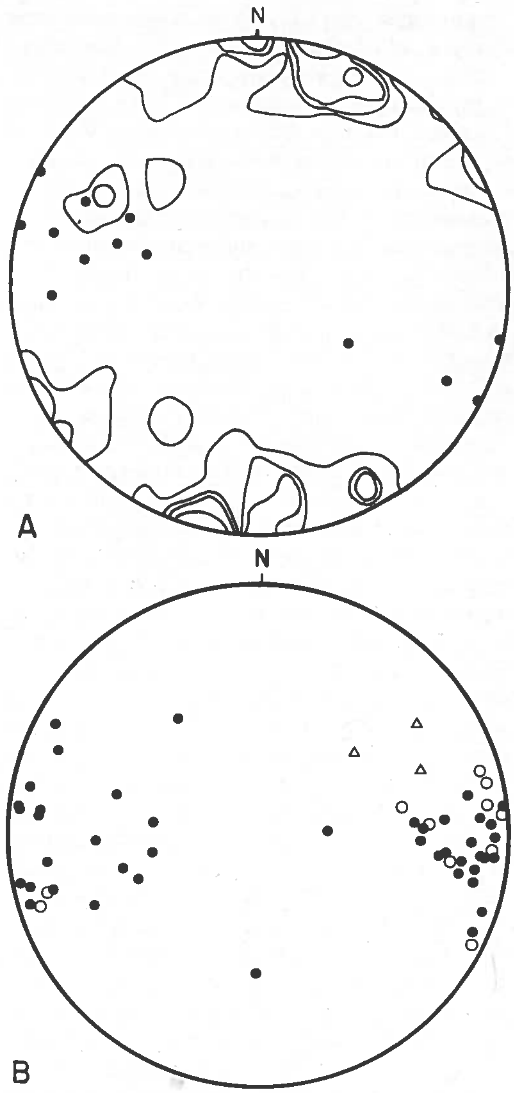

Fig. 8: Equal-area plots of D_2 fabric data.
a. Middagstind shear some Contours: 36 poles to shear zones, contours are 1, 5, 7 and 1144 area. Points: Hornblende lineation in shear zones.
b. D_2 linear structures from throughout east Hinnøy: 43 amphibole lineations (closed circles), 11 stretching lineations (open circles), and 3 boudin axes (open triangles).

Boudinage of schist and amphibolite layers within Evenes Group marble, believed to result from stretching in the limbs of F_2 folds, has been recognized locally. The boudins are generally not well exposed in three dimensions, but three measurements were made in Evenes Group rocks west of Fjelldal (Fig. 8b). These measurements are consistent with the elongation direction inferred from F_2 separation angle.

Thrust Faults. Two D_2 thrust zones have been mapped in the study area: the Austerfjord Thrust, named and described by Hakkinen (1977) from the western edge of Plate 1, and the Vikeland Thrust, a similar structure at the head of Kvæfjord. These shear zones may connect beneath the surface, but this cannot yet be demonstrated. The thrusts are characterized by zones of mild to intense, high-temperature mylonitization from a few metres to hundreds of metres thick. The mylonitic fabric is commonly well developed in the hanging wall, while mylonitic effects die out rapidly downward in the foot-wall. As noted by Hakkinen, these thrust zones are synmetamorphic. No retrograde metamorphism is concentrated along the contacts, and there is no contrast in metamorphic grade across them. Unlice the D_1 thrusts, these thrusts do not juxtapose rocks formed in completely different settings. Nonetheless, displacements on the order of tens of kilometres are possible. The thrusts may be viewed as marking the accretion, to the base of the nappe stack, of sheets detached from the upper part of the basement. Field evidence indicates that this detachment occurred after emplacement of the cover nappes upon the Lofoten block, because thrusts that bound the cover nappes are deformed by D_2 structures.

The Austerfjord Thrust, where described by Hakkinen (1977), places Archaean gneisses upon Proterozoic Austerfjord Group metasedimentary rocks and the 1400 Ma Lodingen Ghranite. Hakkinen considered this thrust to reflect the juxtaposition of two distinct basement terranes of different ages, and as a thrust of potentially major transport. However, close examination indicates that in some areas the mylonitic shear zone lies within the basement gneisses rather than at the gneiss/Austerfjord Group contact. Directly west of Tverrfjell, granite gneiss directly above the Austerfjord Group quartzite and amphibolite is only mildly foliated for a few hundred meters upward. The granite gneiss then grades upward into fine-grained blastomylonite at the summit of Tverrfjell, suggesting that the main movement was localized within the granite gneiss at a higher structural level.

In the present study, the Austerfjord Thrust was traced southeastward across Tjeldsund to its intersection with other Caledonian structures. Relationships in the Fjelldal area, described in detail in Bartley (1982a), are of vital importance for an understanding of the Austerfjord Thrust for three reasons: (1) the Austerfjord Thrust involves Evenes Group rocks here, demonstrating unequivocally that it is of Caledonian age; (2) Storvann Group rocks occur on both sides of the thrust (Bartley 1982a), thus supporting the conclusion that the Austerfjord Thrust does not juxtapose once widely separated terranes; and (3) the Tjeldsund Thrust is deformed by the Austerfjord Thrust, so that the latter post-dates emplacement of at least some of the Caledonian cover allochthons, and is probably a D_2 structure.

Because F_3 folds deform the Austerfjord Thrust and fabrics related to it (Plates 1 & 2), the thrust pre-dates D_3. However, strict synchroneity of the Austerfjord Thrust with F_2 folds of other parts of the study area is difficult to prove. Two lines of evidence suggest this is true. Hakkinen (1977) found that his F_1 isoclinal fold-phase and movement of the Austerfjord Thrust were inseparable in time. The thrust is rarely folded by his F_1 folds, but the mylonitic fabric of the thrust and the axial-planar schistosity of the folds are concordant and continuous with one another. Consequently, the deformations must have been essentially synchronous. If the dominant phase of Caledonian isoclinal folding in the Austerfjord area can be correlated with a similar phase (F_2 in this study) several kilometres to the east, the Austerfjord Thrust should belong to the D_2 of the present study.

A second argument is based on spatial considerations. Between Harstad and Storvann (S), a set of large F_2 recumbent folds represent a significant amount of southeast-directed shear involving both cover and basement. These folds plunge under a large, mildly deformed slab of Precambrian basement to the south of Storvann (S). When the equivalent structural level reappears on the other side of the broad F_3 synform in which the basement slab rests, a discrete ductile shear zone, the Austerfjord Thrust, is present between upper and lower blocks of mildly deformed basement granite. It appears that the same shear strain, distributed through a stack of fold nappes in the northeastern part of the area, has in the southwestern part of the area been concentrated at a single horizon as a ductile thrust. This implies synchroneity of F_2 folding and movement on the Austerfjord Thrust.

Shear Zones at Middagstind. Zones of intense foliation occur (1) within the contact aureole on the east and southeast sides of the Middagstind Quartz Syenite, (2) locally at the contact, and (3) sparsely within the pluton itself. The shear zones vary in thickness from a few centimetres to a few tens of metres, in one case reaching 500 metres. In the mafic rocks of the contact aureole, the shear zones are characterized by weak to strong hornblende alignment. The shear zones at the contact retrogress the otherwise orthopyroxene-bearing hornfels to amphibolite-facies assemblages (Bartley 1981a). In the syenite, the rare shear zones are only a few centimetres thick, except for a zone of mylonitic augen gneiss on the south side of the pluton, which is a 100 m thick. No lineation was apparent in the shear zones within the syenite. The foliation in the shear zones within the syenite is defined by biotite alignment and feldspar elongation. The fabric is developed by cataclasis and recrystallization of feldspars, and recrystallization of quartz and biotite.

In Fig. 8a, poles to shear zones are contoured and measurements of associated hornblende lineations are plotted. The dominant shear set is subvertical, striking N70W, and the hornblende lineation generally has a low plunge within this plane. These data suggest transcurrent displacement along the shear zones. The zones may represent ductile tear faults in the hanging wall of the Austerfjord Thrust. Unfortunately, no markers were recognized to allow displacements to be determined.

Occasional exposures of black flint-like ultramylonite occur west and east of Storvann(s). The ultramylonite zones are discontinous, subvertical, and contain a subhorizontal lineation. These shear zones may be related to the shear zones at Middagstind, and perhaps have similar kinematic significance.

The similarity of the apparent shear direction of these shear zones to that inferred from D_2 folds, boudinage and lineations (see below), and the evidence that the zones formed at amphibolite-facies conditions, support the interpretation that the shear zones are D_2 structures.

Fabrics. Two main fabric elements formed during D_2: a schistosity, S_2, and a sporadic amphibole lineation, L_2. Rarely, a stretching lineation is also preserved. The intensity of the S_2 schistosity depend at least partly upon lithology. Small-scale F_2 folds in micaceous rocks generally show a foliation passing through their hinges to form an intersection lineation with S_1. However, the Stangnes amphibolite, although strongly folded by F_2, seldom shows overprinting of the S_1 schistosity by a second pervasive schistosity (a later S_3 or S_4 spaced cleavage is rarely present). In schists containing both hornblende and biotite, usually only biotite has grown in the S_2 foliation, although both minerals appear to have recrystallized (Fig. 4a). Some thin-sections of Storvann Group schists suggest that new mica growth did not always occur during F_2. Fig. 4b shows a set of micro-folds that deform the primary schistosity with only incipient new mica growth parallel to the axial surfaces. The folds are helicitically overgrown by randomly-oriented plagioclase prophyroblasts, which are in turn truncated by the S_3 spaced cleavage. It is possible that these folds belong to a third pre-porphyroblast fold phase, otherwise unrecognized, but this seems unlikely. Thus, the folds are assigned to F_2, indicating that even in micaceous rocks S_2 may not always be present.

The orientation of L_2 hornblende and stretching lineations reinforces the interpretation that the D_2 shear direction was toward ESE. The amphibole lineation is variably present, and is assumed to have the same kinematic significance as a stretching lineation, that is, the long axis of amphibole crystals parallels the maximum finite elongation direction. This is supported by approximate coincidence of the measurements of amphibole and stretching lineations (Fig. 8b). The attitudes cluster in an east–west trend, with mainly low plunges. As discussed elswhere, S_2 was subhorizontal prior to F_2, and therefore L_2 also formed in a subhorizontal orientation. It is thus likely that measurements with low plunges are only weakly reoriented by later deformation. Rarely, a stretching lineation defined by elongation of quartz and feldspar grains is preserved in quartzites and granite gneiss (Fig. 8b). It is similar in orientation to the amphibole lineation, but bears slightly north of east. This may reflect the small data set, or may indicate that the lineation records superposed strains.

D_2: Cross folding

Major Folds. There are four major F_3 folds in the area of Plate 1. A northwest-plunging basement-cored synform runs from the southeastern corner of the map across Tjeldsund to the Middagstind area (Plate 1). The synformal geometry of this fold is defined by foliation attitudes. Basement granite gneiss in the core of this synform structurally overlies cover rocks southeast of Tjeldsund near Fjelldal. Minor F_3 folds and associated

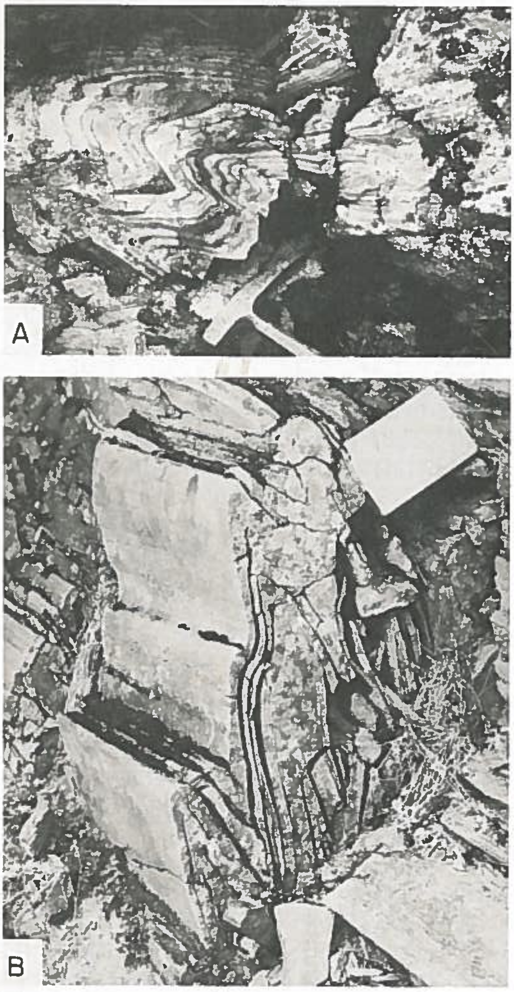

Fig. 9: F_3 fold styles in (a) Storvann Group quartzite, near Kvæfjord, and (b) Storvann Group marble, near Tjeldsund (notebook is 18 cm long).

lineations plunge to the north in the Fjelldal area (Plates 1 & 3), further confirming this geometry. Northeast of this synform is an overturned antiform which can be traced from Tjeldsund across the Storvann Fault to the west side of Finnslettheia. Northward connection of this antiform to the open antiform at Straumsbotn is reasonable, but somewhat speculative because outcrop is poor in the intervening area. In Gustavson's cross-section across the trace of this antiform (1972, p. 23, Fig. 29), this fold is shown as a synform, implying that the basement-cored fold to the south is an antiform. In addition to the evidence already discussed, fabric relationships at the east shore of Storvann (S) and along Tjeldsund support the present interpretation that the basement-cored fold is a synform. S_3 cleavage consistently dips shallowly to moderately north while the S_2 schistosity dips steeply north at the contact. The belt of steep dip is thus the steep limb of a fold couple with the antiform to the north and the synform to the south (see Plate 2, A–A', E–E').

Two more broad F_3 folds are present farther to the northeast. The synform is not well defined, but can be recognized as a broad structural depression in the vicinity of Finnslettheia (Plate 2, D–D'). The antiform to the north is more clearly expressed on the map as a nose of Storvann Group rocks into the basement 3 km east from Straumsbotn. This northern F_3 antiform is refolded by F_4 folds such that the fold locally plunges as much as 70°NW. F_4 folding is dominant northeast of here, and macroscopic F_3 folds have not been identified.

Mesoscopic Folds. Within the cover rocks and much of the adjacent strongly foliated basement, mesoscopic F_3 folds are abundant. These folds correspond to the NW-trending F_2 folds of Gustavson (1972, Fig. 15). The style of F_3 folds changes markedly from one lithology to another (Fig. 9). In schists and quartzites, the F_3 folds are kink-like or chevron folds, usually sharp-hinged and straight-limbed, with long subhorizontal limbs and short, steep limbs. Folds in the Stangnes amphibolite are geometrically similar to those in the schists, but lack the axial-plane cleavage common in the micaceous rocks. In marbles, the F_3 folds are tighter and more sinusoidal. Axial-plane cleavage is weak to absent in marbles. The strongly foliated Precambrian granite near the contacts with the metasedimentary cover rocks folds much like the cover rocks, but the style is more concentric, grading toward chevron folds.

Plate 3 summarizes fabric data pertinent to the late fold phases, F_3 and F_4. F_3 and F_4 are plotted together, because they are not separable on the basis of outcrop criteria, aside from orientation. Gustavson (1972) included these folds in a single phase. Fabric data discussed below suggests a small separation in time between F_3 and F_4 folds on Hinnøy, but Gustavson is probably correct that the northwest- and northeast-trending folds formed nearly synchronously. All subareas except A, C and M are dominated by F_3 (Plate 3). The following general characteristics of F_3 are illustrated by these data: (1) F_3 folds are roughly homoaxial, trend mainly WNW–ESE and have low plunges, mainly less than 20°; (2) S_3 cleavage usually dips moderately to steeply northward, consistent with southward vergence of the major structures; and (3) S_2 poles form fairly complete great-circle girdles, usually with a low-plunging point-maximum reflecting steep limbs and a steep-plunging point maximum reflecting low-dipping limbs. The fabric data are consistent with tight folds, and cylindrical rather than conical shapes. As noted above, the shallow plunge of F_3 and F_4 fold axes, regardless of trend, probably indicates that S_2 prior to F_3 must have been nearly planar and horizontal. The homoaxial character of the folds indicates an absence of major heterogeneities in the deformation pattern during D_3.

Fabrics. Two main fabric elements developed during F_3 folding: S_3, a weak to strong spaced cleavage, and L_3, a strong intersection–lineation between S_2 and S_3 (often recognizable even when S_3 is poorly developed). The S_3 cleavage is strongest in micaceous schists, where it can be the dominant foliation in outcrop. S_3 is seldom well-developed in marbles, presumably due to scarse mica. Mica grains in marble are generally rotated into parallelism with S_3, with some minor flattening of carbonate grains, but S_3 usually is difficult to measure in the field in marbles. S_3 is generally absent in amphibolites. This is presumably due to absence of micas and

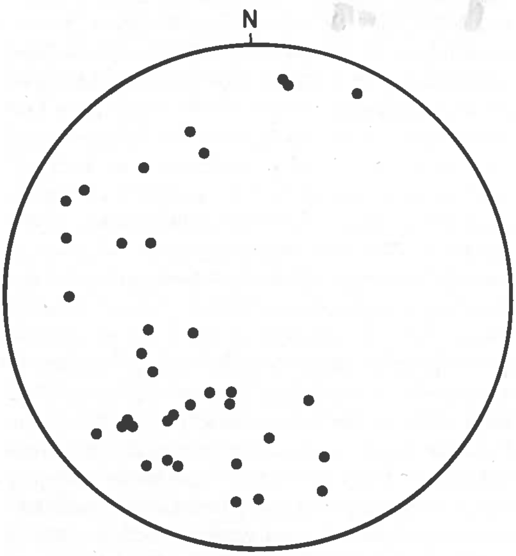

Fig. 10. Equal-area plot of poles to foliation in D_3 (?) shear zones in the basement south of Storvann (S).

quartz which are the main minerals involved in formation of S_3. Some of the granitoid rocks contain S_3 as a prominent secondary biotite foliation crossing the main schistosity.

The S_3 cleavage formed by a combination of solution and recrystallization processes. In thin-section, cleavage traces are discrete surfaces, spaced a few mm apart, along which earlier grains are bent and/or truncated (Fig. 4b). Where garnets are intersected by S_3 cleavage surfaces, they are retrograded to chlorite. New growth of chlorite, biotite, and muscovite has occurred along these surfaces, but grain truncations such as that of the plagioclase porphyroblast in Fig. 4b suggest that solution removal also probably occurred. The textural evidence supports the interpretation that S_3 cleavage formed under upper greenschist-facies conditions, with chlorite and biotite as the dominant pelitic minerals.

Shear Zones in the Basement Gneiss. As the early Caledonian fabrics become less prominent in the basement, mesoscopic F_3 folds disappear. However, southwest of Storvann (S) where the major basement-cored F_3 synform is overturned, spatial adjustments in the core of this fold probably were accommodated by the formation of shear zones in the gneiss.

The shear zones are mainly composed of a brown-weathering schistose rock, formed by grain-size reduction of the granite and mobilization of quartz to produce veins which are often large abundant. The zones range in thickness from 10 centimetres to perhaps 500 metres, but most commonly from 50 to 200 m. They commonly weather to areas of flaggy blocks. The zones may end abruptly, with dilatant voids accommodated by large knots of vein quartz (up to several metres across). In thin-section, cracked feldspar porphyroclasts lie in a matrix of fine-grained quartz, white mica, epidote, and biotite. Micas are kinked, and undulose extinction is common in quartz. The rocks appear to have deformed under conditions allowing relatively little recrystallization.

Orientations of the shear zones are plotted in Fig. 10. The data are highly scattered, and are compatible with a relationship to either D_2 or D_3. However, the apparent late-metamorphic nature of the zones, and the location of the zones in the core of a tight F_3 synform, suggest that they developed during D_3 in massive basement rocks unable to deform by penetrative flow.

Significance of F_3 Cross-folds. The transverse orientation of the F_3 cross-folds is puzzling in the context of the overall structural picture. The concentric and kink-fold geometry and periodic spacing of most F_3 folds indicate that they probably formed by buckling. There is no evidence that they have been rotated by superposed strain. The folds are nearly homoaxial, and the surface folded was subhorizontal prior to folding. The regional maximum shortening direction during D_3 thus was very likely at a small angle to the trend of the orogen.

The F_3 folds thus appear to record a major change in the orientation of the regional strain field experienced by this area. One explanation of this would be a transition from simple convergence to transpression (Harland 1971), a combination of transcurrent and convergent motion along an plate boundary. If the F_3 folds were produced by transpression, the sense of shear would be sinistral. The southward vergence, i e., away from the probable position of any actual strike-slip boundary, is also consistent with a transpressional origin (cf. Odonne & Vialon 1983). Both late Devonian and Carboniferous sinistral movements have been widely suggested for other parts of the Caledonide orogen (Holgate 1969, Kent & Oppdyke 1978, Van der Voo et al. 1979, Van der Voo & Scotese 1981). Major Devonian transcurrent movements have also been inferred to explain the relationships of the Devonian basins of West Norway (Nilsen 1968, Steel 1976, Roberts 1983). The timing of the cross-folds is critical. Because new biotite grew in S_3, biotite-whole rock ages of 360 Ma from cover rocks (Bartley 1980) place D_3 no later than about 360 Ma, i.e., late Devonian. While the suggestion that the F_3 cross-folds represent sinistral transcurrent shear remains speculative in the absence of other evidence for sinistral displacements in the northern Caledonides, the kinematic pattern of the folds must somehow reflect the large-scale tectonic pattern. This possibility thus deserves further investigation.

D_4: Upright Folds

Structures formed in D_4 closely resemble those of D_3, comprising upright to overturned folds, but with a NE–SW axial trend. F_4 was probably nearly synchronous with F_3, but appears to postdate F_3 slightly on east Hinnøy. Poles to S_3 describe a girdle stereographic plots from subareas where both are present (Plate 3, subareas A & C), suggesting that D_3 structures are folded by F_4.

F_4 is more locally developed than F_3, appearing primarily in the northeastern part of the study area and to a lesser extent in the southwestern corner (Plates 1 & 3). Fold styles are much the same as F_3 folds. Vergence of F_4 folds is variable, although F_4 appear to be mainly northwest-vergent backfolds (Steltenpohl & Bartley, 1983). On the south side of the Stangnes penisula, F_4 minor folds are overturned to the southeast, while F_4 folds east of Storvann (N) are overturned to the northwest (Plate 2, B–B').

It appears likely that the intensity of F_4 folding is inversely related to the amount of F_3 distortion of earlier S-surfaces. Strong F_3 folding yielded a configuration analogous to corrugated sheet-metal, that is, resistant to buckling along an axis at a high angle to the corrugations. F_4 folds thus formed preferentially in areas of weak F_3 folding.

Discussion

STRUCTURAL POSITION OF THE LOFOTEN BLOCK

The results of this study support the interpretation that the Caledonian cover allochthons were emplaced over the Lofoten block, and that the nappes were at amphibolite-facies metamorphic conditions after and probably during emplacement. Rocks of the hanging wall of the Austerfjord Thrust belong to the Lofoten block (Hakkinen 1977, Bartley 1981a). The Tysfjord granite, which lies in the footwall of the Austerfjord Thrust, underlies the nappes in the Fjelldal area at the southeast corner of the map area and southward across Ofotfjord to the Tysfjord area. The mineralogy and geochemistry of the Tysfjord Granite suggests that it comprises retrograded mangerite and charnockite of the Lofoten block (Malm & Ormaasen 1978, Schubert & Bartley in prep.). Probable correlatives of the Archaean migmatites of Lofoten have recently been found as xenoliths in the Tysfjord granite at Tysfjord (Bartley, unpubl. data). Further, as noted above, Storvann Group rocks occur on both sides of the Austerfjord Thrust. Thus, the Lofoten block appear to comprise the same basement that underlies the cover nappes. Given evidence that the cover allochthons contain rocks formed in an oceanic setting, rooting of the nappes beneath the Lofoten block would require Caledonian suturing of the Lofoten block to the Baltic craton. Thus, it appears that the nappes were emplaced across the Lofoten block.

Several lines of evidence indicate that the emplacement of the nappes and the Lofoten basement occurred prior to or synchronous with the peak kyanite-grade metemorphism. We have not observed features of retrograde metemorphism concentrated along the contact between cover and basement. The Austerfjord Group, which is intruded by the Lødingen Granite and thus is part of the Lofoten block, was metamorphosed to kyanite grade in the Caledonian (Hakkinen 1977). Geothermometry and geobarometry on pelitic schists of the Austerfjord Group gives P–T estimates of about 550° and 6–8 kb (P. Crowley, pers. comm. 1983), consistent with results from the overlying cover allochthons (Hodges 1982b). Hornblende $^{40}Ar/^{39}Ar$ data from amphibolites within the Lofoten basement do not yield plateau ages because of large amounts of excess ^{40}Ar, but show strong Caledonian disturbance (J. Sutter & Bartley, unpubl. data). This requires that the Lofoten block experienced temperatures during the Caledonian in excess of the closure temperature of hornblende, about 500°C (e.g., Harrison & McDougall 1980). Oxygen-isotope geothermometry on rocks from Caledonian shear zones in the Western Gneiss Region on Senja (50 km northeast of the study area) indicates temperatures during shearing of about 600°C (Cumbest et al. 1983). The lack of Caledonian overprint in large areas of the Lofoten block is thus not due to low temperature during Caledonian time. Bartley (1982a) suggested that infiltration of basement rocks by water, derived from the dehydrating cover, may have caused hydrolytic weakening (Tullis & Yund 1980) and reaction softening (White & Knipe 1978) of the basement. This would concentrate strain in basement rocks close to the basement-cover contact, consistent with the relationships described on Hinnøy and regionally. The Austerfjord Thrust may have formed by a similar process, with the water source being Caledonian metamorphism of the Austerfjord Group metasedimentary rocks.

This interpretation broadly agrees with models showing Norwegian basement massifs as parautochthonous (e.g. Roberts & Gee 1981b, Björklund, in press). It is clear that second-order thrusts, such as the Frostisen Thrust (Hodges et al. 1982), appear to represent a significant amount of basement shortening. The evidence summarized above appear to preclude interpretation of the Lofoten block as a far-travelled nappe, but on the other hand, these rocks cannot be concidered to be strictly autochthonous.

TIME OF NAPPE EMPLACEMENT

The classic Caledonian orogeny in southern Scandinavia ('Scandian' or 'Scandinavian' orogeny) is placed in Silurian time on the basis of stratigraphic relationships (Strand & Kulling 1972, Gee 1975). However, in recent years Sturt et al. (1967, 1975, 1978) have emphasized the importance of the 'Finnmarkian phase', a late Cambrian–early Ordovician period of deformation and plutonism first recognized in northernmost Norway. An early orogenic phase has also been recognized in southen Norway, which has been correlated with the Finnmarkian phase recognized further north (Sturt & Thon 1976). It has been suggested that the Finnmarkian phase was responsible for much of the penetrative deformation and medium- to high-grade metamorphism in the northern Scandinavian Caledonides, particularly in the Lower and Middle Allochthons (Roberts & Gee 1981a).

Geochronologic data are as yet inadequate to resolve precisely the age of the deformation and metamorphism described from the present area. Rb/Sr, K/Ar and $^{40}Ar/^{39}Ar$ mica ages from Hinnøy range from 390 to 347 Ma (Bartley 1980, 1981a, Hodges et al. 1980, J. Sutter, pers, comm. 1980) and reflect post-Scandian uplift. K/Ar hornblende ages for the Efjord area average about 450 Ma (Hodges 1982a), but as noted earlier, the ages must be interpreted cautiously because all $^{40}Ar/^{39}Ar$ studies in the Norwegian Caledonides to date have revealed the presence of significant amounts of excess ^{40}Ar in both basement and cover rocks.

The possible correlation of the Evenes Group with the Ordovician–Silurian rocks of the Balsfjord Supergroup is thus critical. Recent studies (Steltenpohl & Bartley 1984, Steltenpohl in prep.) imply that all of Hinnøy and adjacent Ofoten experienced kyanite-grade conditions in the Caledonian, including much or all of the Evenes Group. This suggests that stacking of the cover allochthons predated the end of the metamorphic peak. Two possibilities are thus defined: 1) The Evenes Group correlates with the Balsfjord Supergroup, and all the metamorphism and structures distinguished here can be assigned to the Scandian phase; or 2) The

Evenes Group is older than both the Balsfjord Supergroup and the Finnmarkian event, and the metamorphic peak and associated deformation *may* be as old as the Finnmarkian. A less likely third possibility is that the Evenes Group is older than the Balsfjord Supergroup but that all the deformation and metamorphism are nonetheless Scandian. The lithologic resemblance of the Evenes Group to the Balsfjord Supergroup favors the first interpretation, i.e., that the main kyanite-grade metamorphism in this area is Silurian and could be assigned to the Scandian phase.

The evidence that the basement-involved folds and thrusts formed after emplacement of the cover allochthons thus takes on further tectonic significance. If the lower nappes on Hinnøy composed of interleaved Precambrian gneisses and Storvann Group correlate with the Lower or Middle Allochthons (e.g. Björklund 1981), then the deformation, metamorphism and emplacement of the Lower and Middle Allochthons also may be a Silurian event in this area. Regardless of the age of the Evenes Group, the basement-cover geometry requires that the allochthonous Precambrian rocks were detached after the stack of Caledonian cover allochthons was already emplaced. Field relationships on Hinnøy do not support emplacement of a younger Scandian allochthon upon interleaved basement cover comprising Lower and Middle Allochthons already deformed in the Finnmarkian phase (cf. Roberts & Gee 1981a, Boyd 1983).

Summary

The earliest Caledonian tectonic event distinguished on east Hinnøy (D_1) is the emplacement of cover allochthons upon the Precambrian basement of the Lofoten block, with its parautochthonous cover (Storvann Group) at least locally preserved. Subsequently, D_2 ductile shearing of the basement near its contact with the cover interleaved and infolded the basement with the Storvann Group and overlying cover allochthons. This produced at least local inversions of the early nappe stack during D_2. It is possible that considerable transport of the composite allochthon comprising the cover allochthons and the imbricated Storvann Group and basement could have occurred during D_2. Structural analysis indicates that transport during D_2 was in an east–southeast direction. Shortening in a direction nearly parallel to the trend of the Caledonian orogen then ensued, forming prominent south-vergent cross folds, perhaps reflecting left-lateral transpression. Shortening of both cover and basement in the more normal NW–SE direction is expressed by D_4 folds. If the Evenes Group does correlate with the Balsfjord Supergroup and is thus Silurian, all of these events must belong to the Silurian 'Scandian' orogeny. Earlier, possibly Finnmarkian, structures have not been recognized, although such early structures may be difficult to distinguish due to strong later overprinting.

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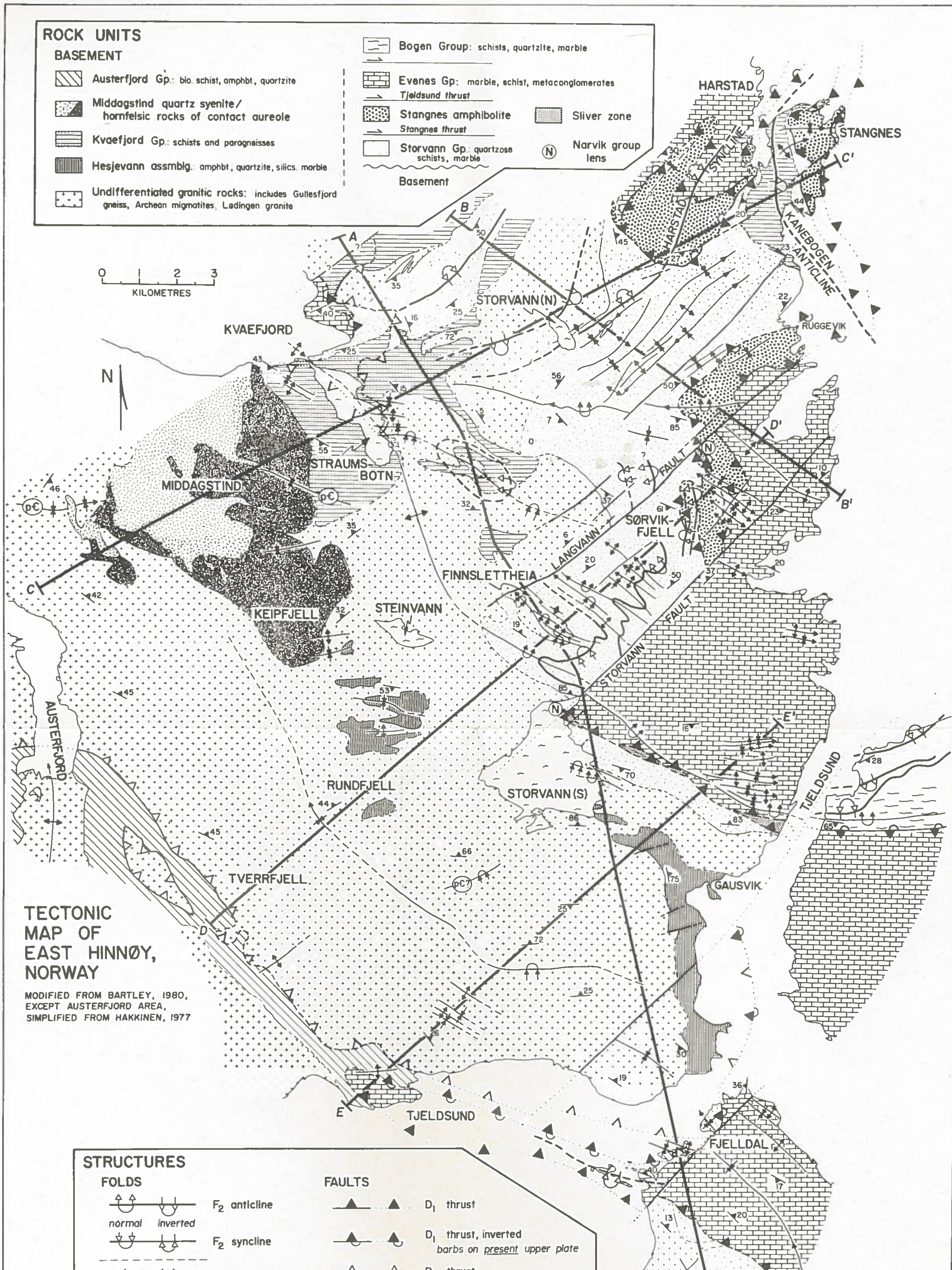

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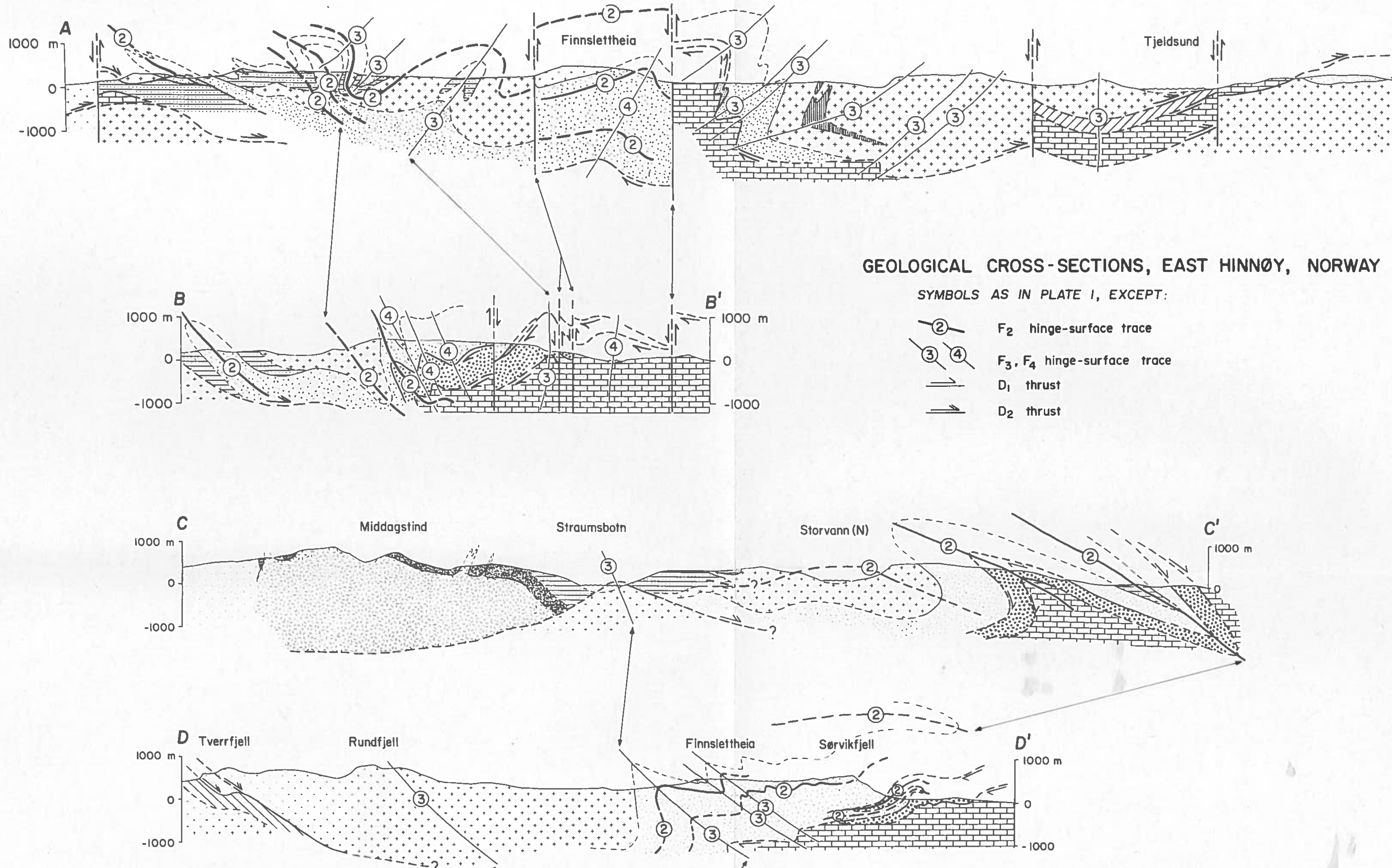
Plate 1: Tectonic map of east Hinnoy.



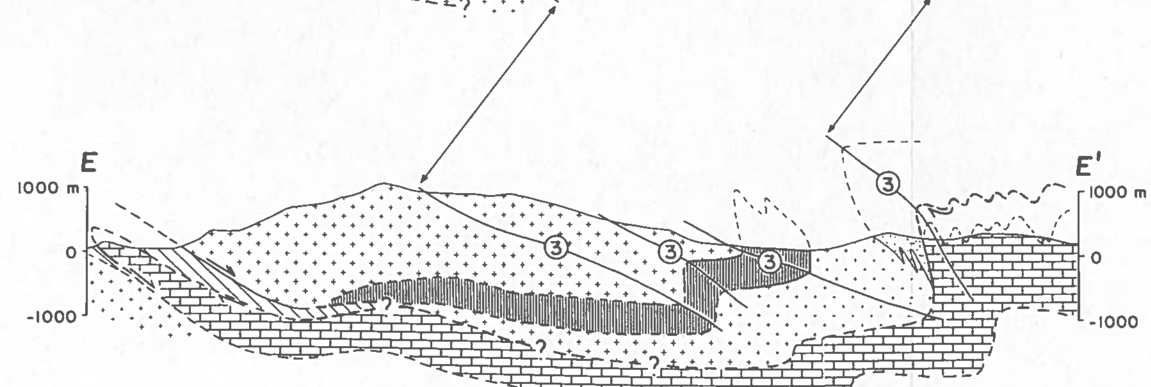


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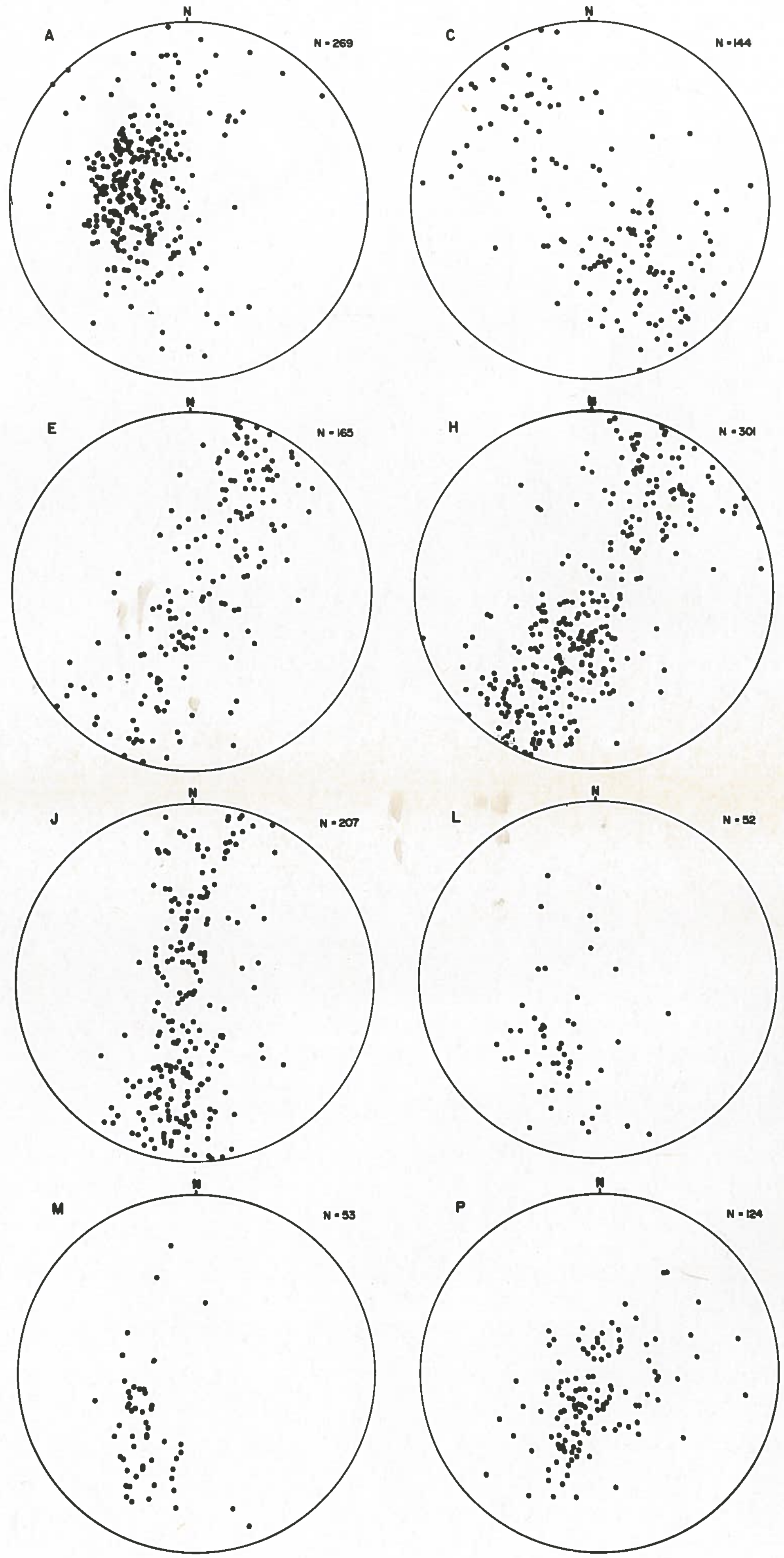
Plate 2: Geological cross-sections of east Hinnøy. See Plate 1 for location.

(a)



(b)

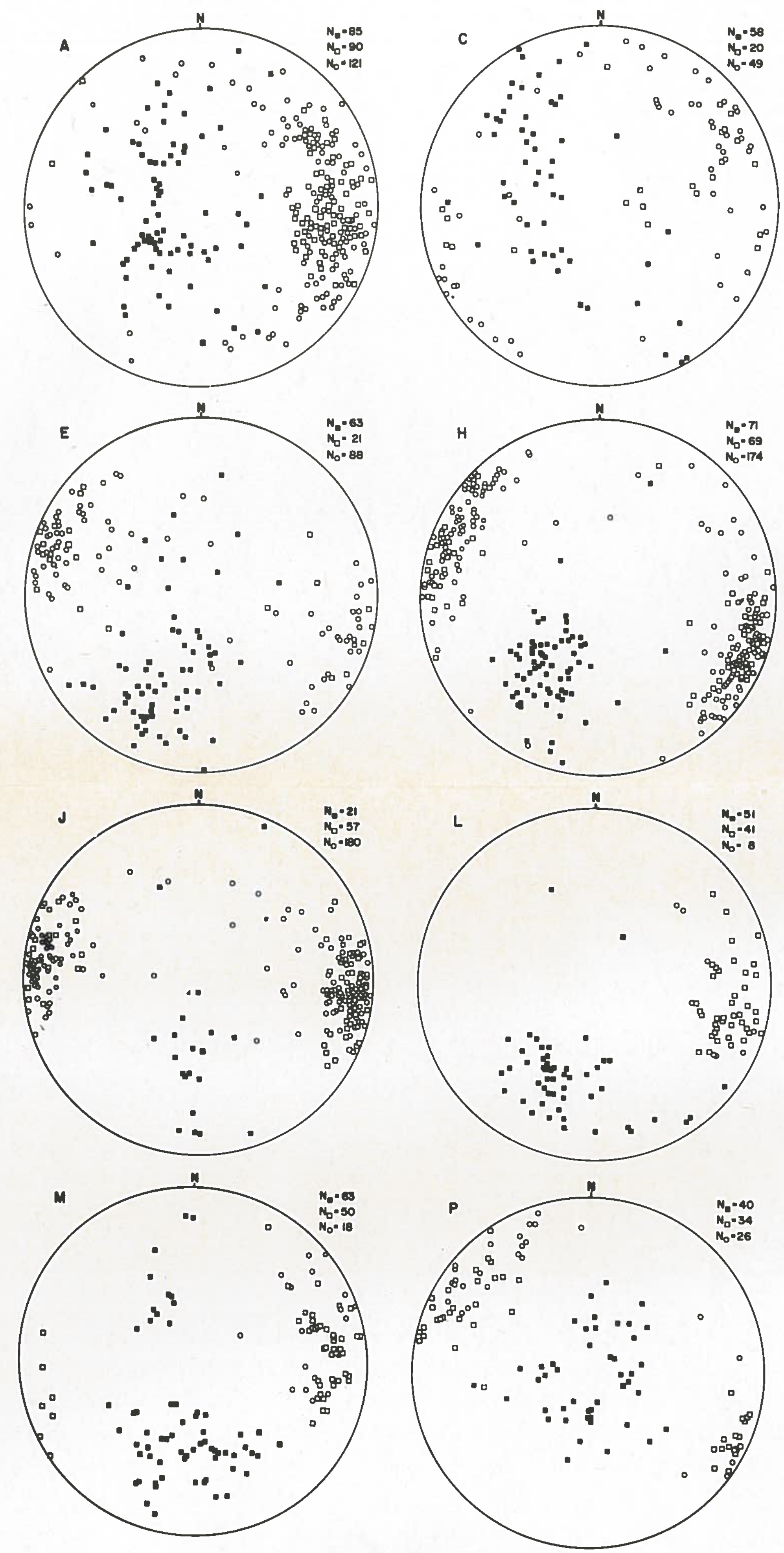


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Plate 3:
a. Equal-area plots of S_1 and S_2 (not separated because typically parallel or subparallel at the outcrop scale as a result of intence D_2 transposition of S_1).
b. Equal-area plots of S_3 (filled squares), F_3 and F_4 fold axes (open circles), and L_{1x3} and L_{1x4} (open squares).