Basement-cover relations and Caledonian tectonostratigraphy of Sandsøya, Grytøya, Åkerøya, and Kjøtta, Western Gneiss Region, North Norway

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Rocks of Sandsøya, Grytøya, Åkerøya, and Kjøtta, represent four Caledonian tectonic settings: (1) pre-Caledonian Baltic crystalline basement of the Western Gneiss Region, including intrusively enclosed supracrustal rocks; (2) an autochthonous/parautochthonous Vendian/Cambrian (?) metasedimentary cover; (3) the Lower/Middle Allochthons and granitoid slivers of Baltic affinity; and (4) the suspect or exotic terranes of the Upper Allochthon. Detailed geologic mapping of these islands indicates Upper Allochthon units have been incorrectly assigned to the Lower/Middle Allochthons on earlier maps. Detailed lithologic observations allow for regional correlations that better define the structural configuration of the west limb of the Ofoten Synform. Slivers of mylonitized granite gneiss overlain by orthoquartzite, graphitic schist, mica schist, and dolomitic/calcitic marble have been recognized. The repetition of these units documents structural imbrication of Precambrian basement and its attached cover. Amphibolite-facies (kyanite grade) mineral assemblages occur within the imbricated basement-cover, documenting intermediate depths of formation. Late- to post-nappe emplacement left-slip plastic shear zones in the basement complex are commonly associated with supracrustal enclaves that parallel the basement-cover contact. Sense-of-shear studies of the basement shear zones combined with shear indicators observed in phyllonitic cover units document top-to-the-northeast, left-slip transport along the shallow southeast-dipping shear zones. Hornblende and muscovite $^{40}Ar/^{39}Ar$ cooling ages of 408 and 391 Ma, respectively, from cover-units combined with microstructural and fabric observations bracket the time of left-slip movement to Late Silurian-Early Devonian. The basement-cover contact and the plastic shear zones are modified by vertical, fluorite-bearing microbreccia zones that reach thicknesses of over 100 m.

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Introduction

The Ofoten region of North Norway is one of the optimal places on Earth to investigate orogenic basement-cover relationships. Recent glaciation and uplift have exposed enormous tracts of deep- to middle-crustal level rocks so that near-equal proportions of basement and cover are exposed (Fig. 1). The basement-cover contact is exposed in three different orogenic settings, the foreland (southeast part of Fig. 1), the Rombak window, and the more internal Western Gneiss Region exposed along the coast. In the foreland, unmetamorphosed parautochthonous cover rocks lie unconformably on autochthonous Precambrian basement of the Baltic Shield. West of the foreland is the Rombak window, a large (250 km^2) tectonic window exposing Precambrian basement gneiss and its attached cover through the eroded Caledonian allochthons. Further west along the present day coast is the Western Gneiss Region, another exposure of Precambrian basement gneiss (Foslie 1941, 1942, Vogt 1942, Andresen & Tull 1986). Rocks of the Rombak window and Western Gneiss Region are thought to be structurally continuous beneath the allochthons lying within the core of the regional Ofoten synform (Fig. 1: Gustavson 1972). These relations, therefore, permit the direct examination of stratigraphic, metamorphic, and deformational variations along the contact between the basement and its autochthonous/parautochthonous/allochthonous cover across nearly the entire width of the orogen.

The evolution of the Western Gneiss Region basement-cover contact in western Ofoten (Fig. 1) is controversial. Three different interpretations have been reported for the same segment of the contact on Hinnøy. Bartley (1984) reported large, >10 km amplitude, basement-cored, Alpine-style ductile folds that he interpreted to have formed at middle- to deep-crustal levels (kyanite-grade conditions) during A-type subduction between Baltica and Laurentia (Hodges et al. 1982). Björklund (1987), on the other hand, reported greenschist-facies rocks caught up in a duplex along the basement-cover contact that, he argued, refutes the idea that this contact is the ancient subduction zone boundary. More recently, Andresen & Rykkelid (1991) and Rykkelid (1992), suggested that the basement-cover contact on Hinnøy is an out-of-sequence thrust that brought greenschist-facies rocks into contact with the higher grade amphibolite-facies units. The basement-cover contact on Hinnøy pro-

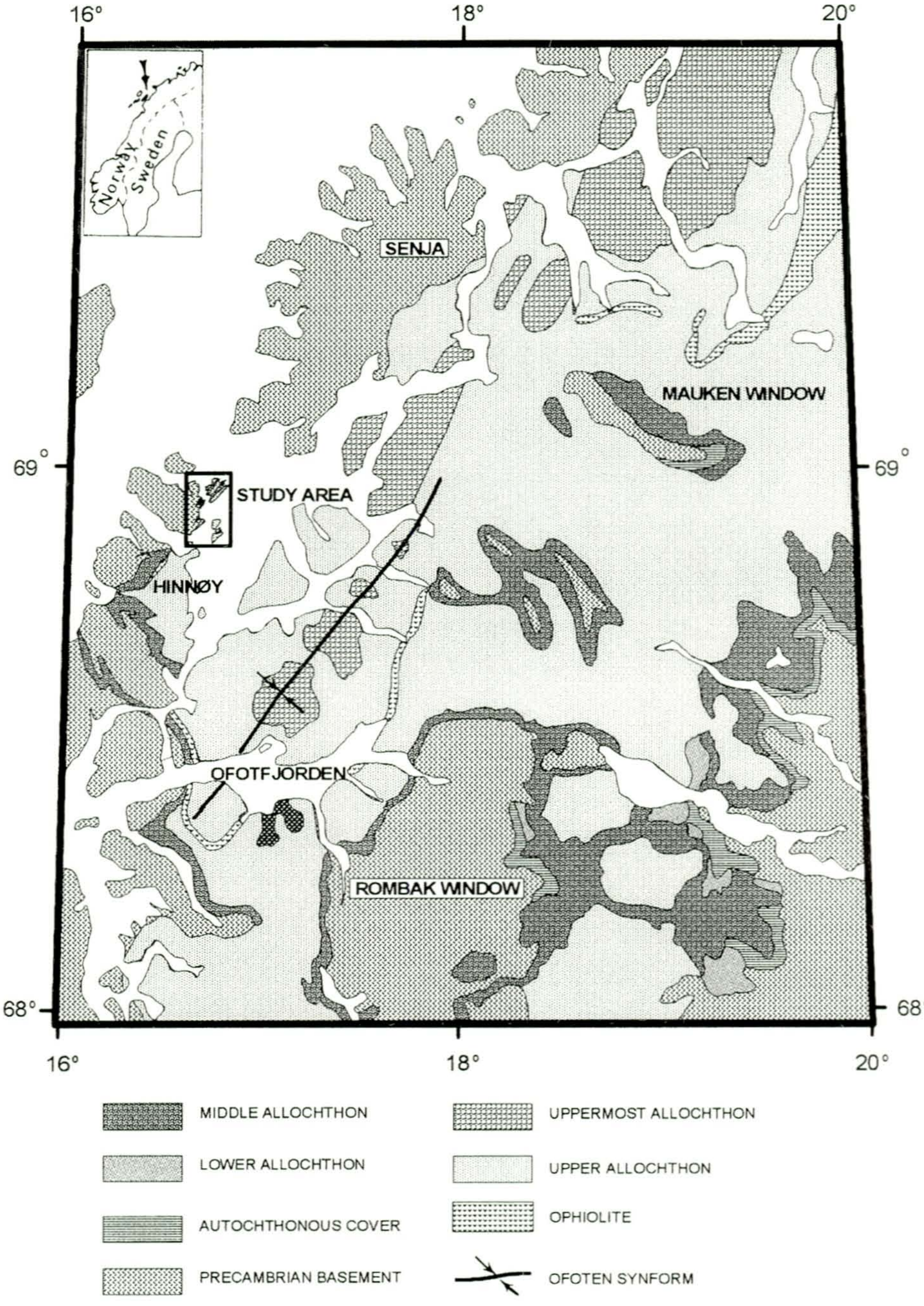

Fig. 1. Generalized tectonic map of the Ofoten region illustrating the location of the study area (modified from Gustavson 1972, Anderson et al. 1992).

jects directly northward onto the islands of Grytøya and Sandsøya (Fig. 1), which are the areas considered in this study. Herein we present: 1) a detailed geological map of Sandsøya and its adjacent islands; 2) our interpretive correlations of units on these islands with rocks throughout the Ofoten region; 3) detailed structural and fabric analyses of rocks along the basement-cover contact as well as from the overlying outboard exotic terranes of the Upper Allochthon; 4) our interpretation of the deformational style along the basement-cover contact; and 5) $^{40}Ar/^{39}Ar$ cooling dates on hornblende and muscovite that, combined with observed microstructural and fabric relations, place constraints on the timing of tectonothermal development of rocks and structures in this area.

Tectonostratigraphy

The tectonostratigraphy is described from the structurally lowest unit, the Tysfjord granite gneiss, southeastward across strike to the structurally highest unit exposed on the northeast shore of Kjøtta, the Købbevika gneiss (Fig. 2). Mappable rock units are informally named after local geographic features. Original, primary thicknesses of

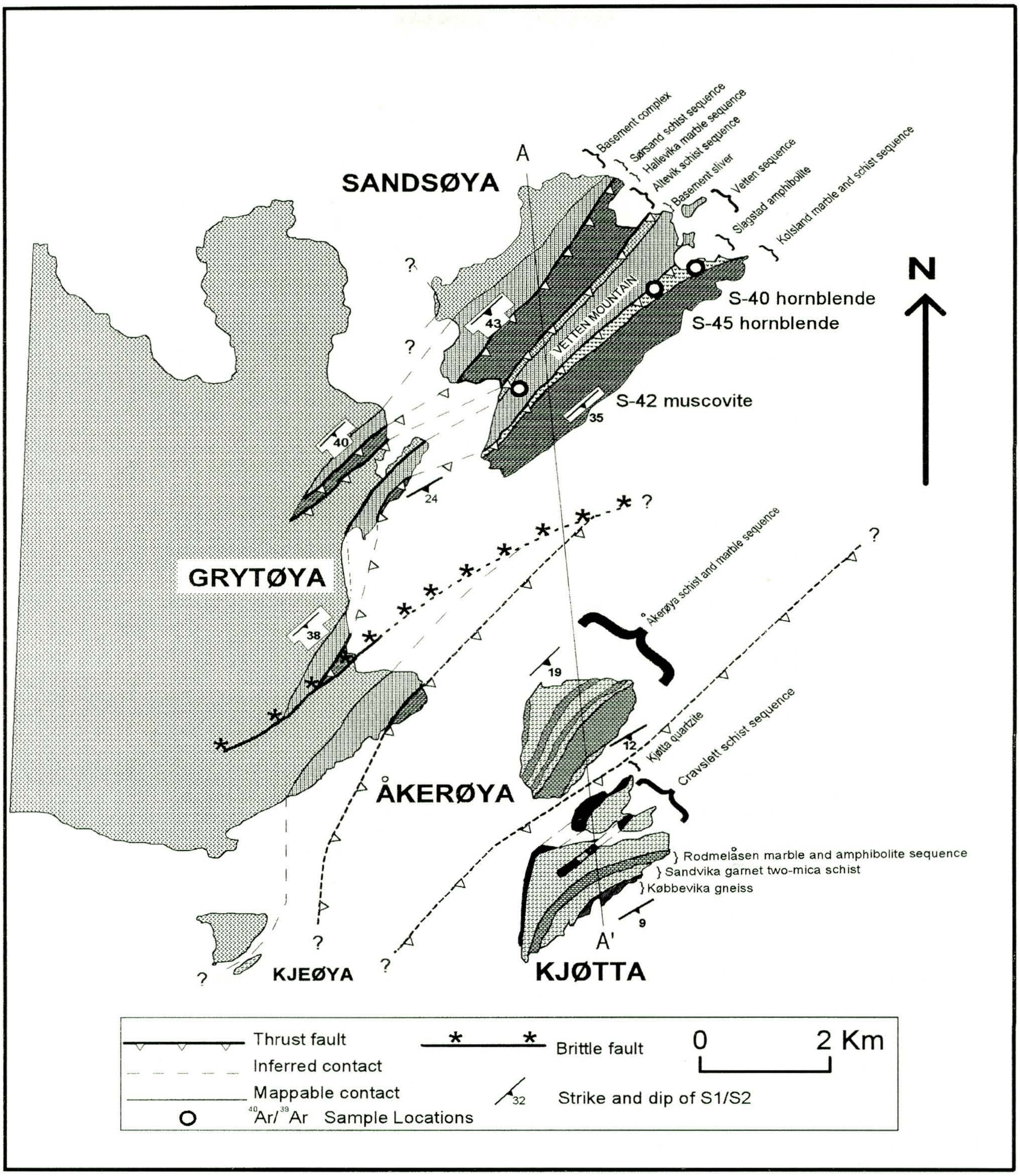

Fig. 2. Lithotectonic map of the study area.

units have been modified by thrusting, localized shearing, isoclinal folding and boudinage, so that these are now apparent thicknesses only. The rocks are described beginning with the dominant rock type in each unit progressing to less voluminous ones. A generalized NW-SE cross-section of the study area (A-A') is shown as Fig. 3.

Basement complex

Rocks of the basement complex are more or less continuously exposed along the west shore of Sandsøya and the northeast shore of Grytøya. The basement complex includes the Tysfjord granite gneiss, supracrustal xeno-

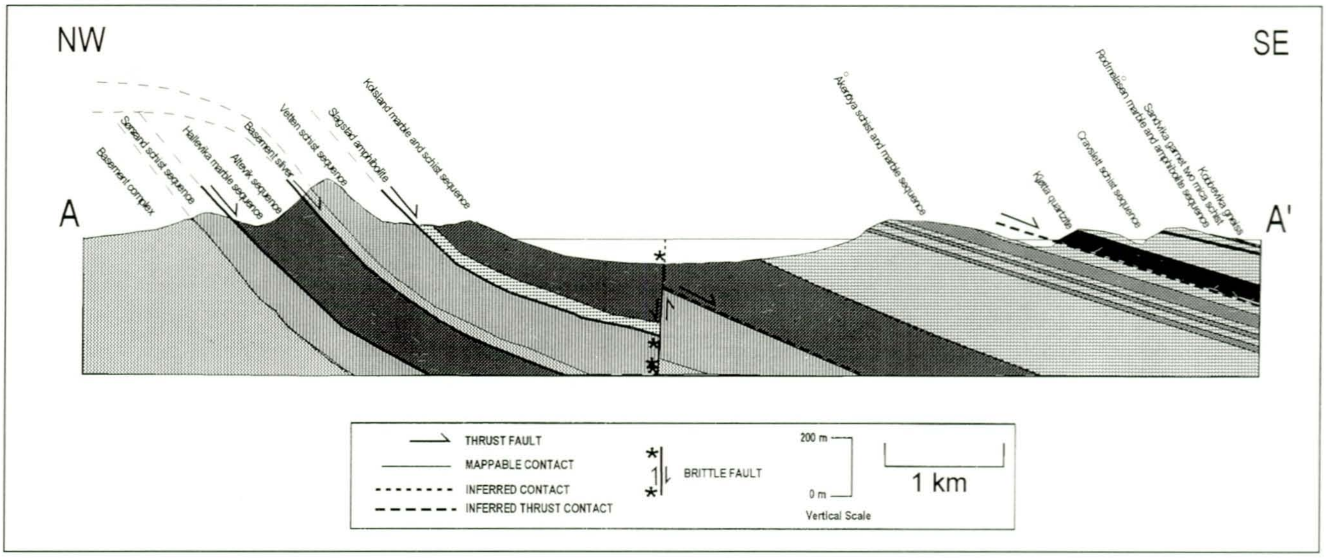

Fig. 3. Generalized NW-SE cross-section from Sandsøya to Kjøtta (A-A'). For line of section, see Fig. 2. Vertical scale is exaggerated (5 X).

liths and enclaves, sulfide-bearing metavolcanics and metasedimentary rocks of the Kråkeneset sequence, and older plutonic units.

Tysfjord granite gneiss. The Tysfjord granite gneiss is the most voluminous unit in the study area. It has a structural thickness of at least 400 m on Sandsøya and constitutes most of Grytøya. Regionally, this unit has been described by Foslie (1941), Gustavson (1966), and Andresen & Tull (1986). The Tysfjord granite gneiss on Sandsøya ranges from a homogeneous, coarse-grained, slightly foliated, microcline-rich granite in the southwest portion of the study area to a recrystallized, fine-grained, quartz-rich biotite mylonitic gneiss, directly below the basement-cover contact on the northeast side of the island. Biotite content increases from the southwest to the northeast portion of the basement complex and is typically accompanied by a reduction in grain size and a decrease in the modal abundance of microcline feldspar. In zones of ductile shearing, the Tysfjord granite gneiss is deformed to a strongly foliated (S-tectonite) orthomylonite. Cross-cutting the gneiss are numerous, thin (<15 cm wide), fine-grained quartz monzonite dikes.

Coarse-grained Tysfjord granite gneiss is generally massive, containing a weak foliation defined by the parallel alignment of biotite grains. Pink microcline (<3 cm in length) characterizes the gneiss, which is typically light pink to gray in color. Modal mineralogy of the gneiss is estimated as microcline (60%), plagioclase (15%), biotite (2-5%), quartz (10-15%), hornblende (4-8%), and accessory fluorite, garnet, apatite, titanite, and epidote.

Orthomylonites identified in the basement complex contain essentially the same mineralogy as the Tysfjord granite gneiss. In areas approaching shear zones, a parallel alignment of biotite and flattened and extended microcline porphyroclasts together define a mylonitic foliation, giving the rock a gneissic appearance. In hand sample the rock is medium- to coarse-grained with 10 to 50% microcline porphyroclasts (<1 cm across). In thin-section, the orthomylonite contains microcline (40%), plagioclase (25%), biotite (15%), quartz (10%), epidote (3-5%), and accessory hornblende, chlorite, calcite, clinozoisite, zoisite, allanite, and apatite. Epidote is concentrated in some shear bands where it may compose more than 60% of the rock, imparting an apple-green color to the rock.

In the northern part of the basement complex, structurally below the basement-cover contact, outcrops of a fine-grained, quartz-rich biotite gneiss are interpreted as dynamically recrystallized Tysfjord granite gneiss. Hand samples of this rock are fine- to medium-grained and dark gray in color. In thin-section the rock has a well-developed grain-shape preferred orientation (GSPO) defined by biotite (40%), plagioclase (35%), quartz (10%), microcline (8%), and epidote (5%).

In several locations in the basement complex, quartz monzonite dikes cross-cut the Tysfjord granite gneiss. The dikes range in thickness from 3 cm to 15 cm and vary in color from gray, tan, to pink-gray. Metamorphism of the dikes and surrounding Tysfjord granite gneiss is interpreted to have been simultaneous on the basis of the parallel alignment of biotite grains that extend through the contact into both units.

Supracrustal units. Supracrustal rocks constitute only a small volumetric portion of the basement complex on the west shore of Sandsøya and the northeast shore of Grytøya. They are enclosed in the Tysfjord granite gneiss as xenoliths and large enclaves. Because these units are metasedimentary or volcanic in origin, and because their original depositional relations are unknown, they are called supracrustal rocks by Caledonian geologists (e.g., Gustavson 1969). The different types of supracrustal rocks recognized in the field area include a fine-grained biotite

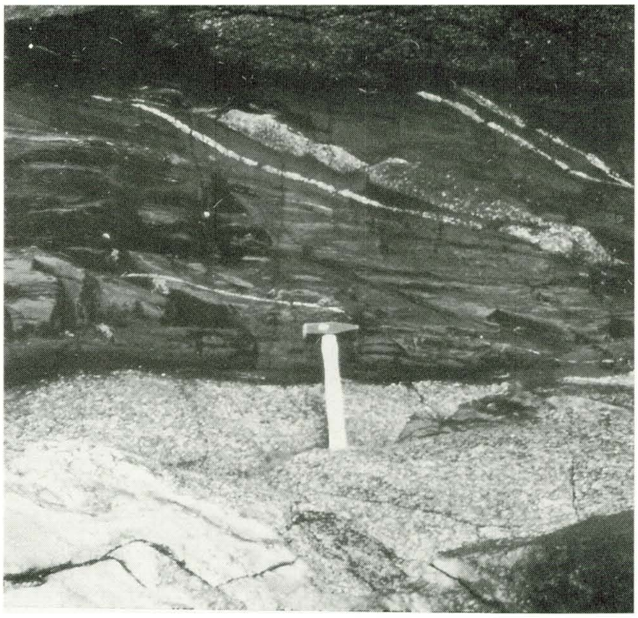

Fig. 4. Outcrop photograph of biotite amphibolite (dark) of the basement complex. Note apophyses of Tysfjord granite (light) in upper and right-central portion of the photograph and a xenolith of biotite amphibolite to the right of the hammer.

Fig. 5. Outcrop photograph of banded meta-arkose, bottom of photograph, within Tysfjord Granite. Note xenolith of meta-arkose in center of photograph.

amphibolite and a banded meta-arkose.

Biotite amphibolite has a structural thickness of approximately 120 m where it crops out directly beneath the basement-cover contact on northern Sandsøya. Locally the amphibolite is intruded by the Tysfjord granite gneiss (Fig. 4). Outcrops of the biotite amphibolite are penetratively deformed and contain a well-developed schistosity defined by biotite and hornblende. Quartz veins (<5 m in strike length) are common in this rock and parallel the dominant foliation. Hand samples are fine- to medium-grained, finely laminated, and black to green in color. The dominant minerals include hornblende (85%), biotite (5%), plagioclase (2-5%), and quartz (3-5%).

Banded meta-arkose occurs as blocky or sheared, lens-shaped xenoliths within the Tysfjord granite gneiss (Fig. 5). Compositional banding defined by centimeter-scale, light and dark layers give the rock a striped appearance. In hand sample the meta-arkose is fine- to medium-grained and light gray to brown in color. In thin-section the lighter colored bands contain microcline (40%), plagioclase (30%), quartz (10-15%), and biotite (2-5%). The darker bands contain the same minerals as above with the addition of hornblende (25%) and epidote group minerals (10%).

Kråkeneset sequence. The Kråkeneset sequence is a roughly tabular, approximately 60 m thick unit of hornfels, amphibolite, epidote-bearing amphibolite, meta-quartz monzodiorite, quartzite, garnet-magnetite-hornblende-bearing biotite phyllonite, epidote-biotite schist, and marble that crops out within the Basement complex on northwest Sandsøya (Fig. 2). These units commonly are bordered by thin, less than 2 m thick, ductile shear zones that juxtapose Tysfjord granite gneiss.

The most abundant rock in the Kråkeneset sequence is approximately 15 m of hornfels. In outcrop the hornfels is massive to weakly foliated and locally weathers to a dark gray or black color. Hand samples are fine-grained, structureless, and dark gray in color. Within the hornfels is a well-foliated, fine- to medium-grained epidote-bearing amphibolite (<3 m thick). The amphibolite unit contains thin quartzite lenses (<5 cm long) that parallel the dominant foliation defined by hornblende and biotite. Apophyses of the Tysfjord granite gneiss intrude the amphibolite.

Older igneous rocks. The older igneous rocks of the Basement complex are rare and are of two types, a fine-grained metagabbro and a younger, coarse-grained granodiorite. Both rock types occur as xenoliths in the Tysfjord granite gneiss on southwest Sandsøya and northeast Grytøya. Several xenoliths of the metagabbro are encapsulated within the granodiorite. Apophyses of the Tysfjord granite gneiss commonly wedge into and crosscut the granodiorite but not the metagabbro, thus establishing the relative age of these plutonic rocks.

Caledonian allochthons

Sørsand schist sequence. Directly above the basement-cover contact on Sandsøya is a 175 to 350 m thick structurally interleaved sequence of orthoquartzite, graphite-bearing phyllonitic schist, biotite-quartzofeldspathic schist, garnet-biotite-quartz schist, biotite-quartz schist,

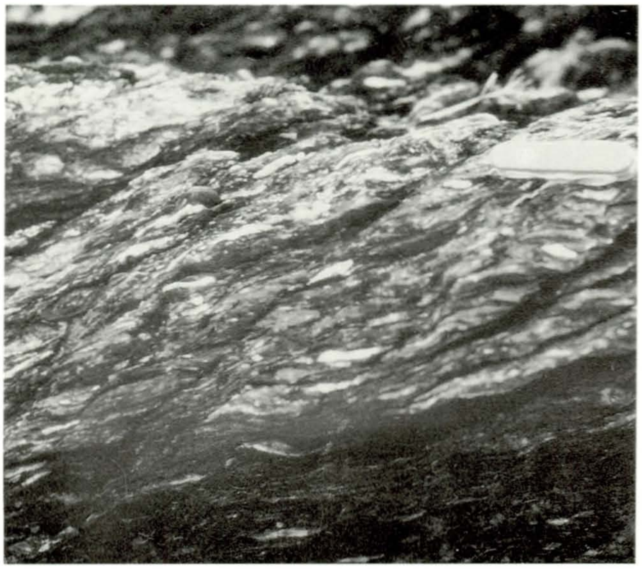

Fig. 6. Outcrop photograph of the phyllonite structurally above the basement-cover contact. Note shear bands (dipping moderately to the left) extending the schistosity (subhorizontal in photograph) and quartzite lenses. View is toward the southeast, looking down dip of the phyllonitic cleavage and parallel to the elongation lineation. Sense of shear is left-slip, top-to-the-northeast.

feldspathic quartzite, and microcline-bearing biotite-quartz meta-arkose which herein is informally called the Sørsand schist sequence.

A 0.5 m thick basal quartzite rests directly upon the mylonitized basement gneiss and marks the basement-cover contact on Sandsøya and Grytøya. The quartzite is fine- to medium-grained, tan to buff colored, and has a moderately well-developed micaceous cleavage along which the rock splits into slabs 3-5 cm thick.

Overlying the basal quartzite is approximately 30 m of interleaved phyllonitic schist and biotite-quartzofeldspathic schist. In outcrop, the phyllonitic schist contains large micaceous `buttons' (<3 cm long) and weathers dark gray to medium brown. Quartz lenses (<6 cm long) parallel the phyllonitic cleavage which is defined by a shear-band foliation along which muscovite and biotite 'fish' are extended. The phyllonitic cleavage itself is crenulated, folded, and locally transposed (Fig. 6). In thin-section this rock contains biotite, muscovite, quartz, and minor plagioclase. Muscovite 'fish' contain fine-grained 'dusty' graphite inclusions.

The biotite-quartzofeldspathic schist contains generally the same mineralogy as the phyllonitic schist although the former has more quartz and plagioclase and less muscovite. In outcrop this rock weathers to a dull gray color and commonly has a pitted appearance due to the dissolution of carbonate grains. Mica 'buttons' (<2 cm long) are common.

Structurally above the biotite-quartzofeldspathic schist is a 140 meter thick section of garnet-biotite-quartz schist. In outcrop this unit weathers medium-bluish gray. Hand samples are fine- to medium-grained and contain visible garnet (<3 mm in diameter). In thin-section the rock contains garnet, biotite, muscovite, quartz, plagioclase, and accessory chlorite, tourmaline, graphite, and calcite. Poikiloblastic garnets commonly have curved inclusion trails of quartz, biotite, and plagioclase that define an S_i fabric that is discordant with the surrounding S_e fabric of the matrix, indicating post-crystallization rotation.

A biotite-quartz schist crops out on southern Sandsøya and is informally called a 'flaser' schist on the basis of large, dark gray biotite-rich lenses (<3 cm long) with a distinctive phacoidal shape that resemble flaser structures found in sedimentary rocks. The flaser schist is approximately 8 m in thickness and weathers to a gray-black color. In thin-section, the dominant mineralogy is biotite, muscovite, microcline, plagioclase, and quartz with accessory calcite, apatite, titanite, and opaques.

A very distinctive, flaggy feldspathic quartzite occurs within the structurally upper parts of the flaser schist. The feldspathic quartzite is generally less than 10 m thick and characteristically parts in slabs roughly 1 to 2 cm thick. Some slabs are itacolumite quartzite, meaning that when hit with a rock hammer it has a springy, elastic feel instead of ringing.

A microcline-bearing biotite-quartzofeldspathic meta-arkose crops out structurally above the 'flaser' schist and the feldspathic quartzite. It has a structural thickness of approximately 10 m and weathers to a dark gray color. Rounded, pink potassium feldspar porphyroclasts (<1 cm long) are sparse, but where present, give the rock a spotted appearance that is diagnostic of this unit. Some of the feldspar clasts are elongated parallel to the dominant foliation.

Hallevika marble sequence. The Hallevika marble sequence crops out structurally above the Sørsand schist sequence. The best outcrops of this unit are found along the south and northwest shores of Sandsøya (Fig. 2). This sequence contains approximately 400 m of dolomitic and calcitic marbles interbedded with dolomitic schist and sparse two-mica schist, garnet-muscovite-biotite schist, quartzite, graphitic schist, and at its base, a banded amphibolite.

Dolomitic marbles range in thickness from 1 to 25 m. Outcrops are generally massive to moderately well banded and weather dark brown-gray to tan in color. Fresh outcrops are usually white, cream, or medium light gray. Hand samples are fine- to coarse-grained, characteristically sugary textured, and locally contain fine-grained muscovite. Thin-sections of the dolomitic marble contain up to 98% dolomite and accessory calcite, muscovite, plagioclase, and quartz.

Outcrops of the calcite marbles commonly weather from cream to dark-gray in massive or moderately banded varieties. Thickness of this unit ranges from 1 to 25 meters. Hand samples are white to blue-gray in color, medium- to coarse-grained and locally have thin lamina

(<1 mm thick) of concentrated and preferentially aligned muscovite. In thin-section these rocks contain calcite (90-95%), with minor amounts of muscovite (3-5%) and assessory plagioclase, quartz, biotite, and opaques.

Dolomitic schist, two-mica carbonate schist, garnet-muscovite-biotite schist, quartzite, amphibolite, and graphitic schist constitute only a small volumetric proportion of the Hallevika sequence. All but the dolomite schist form thin (<10 m thick) discontinuous lenses intercalated within the different marbles. The dolomitic schist ranges from 20 to 60 m in thickness. In outcrop, quartz lenses form narrow, thin ridges (<5 mm thick) giving the unit a ribbed appearance.

The banded amphibolite unit marking the base of the Hallevika sequence ranges in thickness from 0.5 to 2 m and commonly weathers to grayish olive green in moderately banded varieties. Hand samples are fine- to medium-grained and contain a schistosity and mineral lineation defined by the parallel alignment of amphibole grains (<3 mm long). Locally these fabrics are completely transposed by a strong mylonitic fabric.

Altevik schist sequence. The Altevik schist sequence lies structurally above the Hallevika marbles and structurally below the basement sliver that cuts Sandsøya nearly in half (Fig. 2). This sequence is exposed along the southern and northern shores of Sandsøya but is not traceable along strike inland where outcrops are few. Some confusion exists in trying to correlate rocks in this sequence because minor lithologic differences occur in outcrops along the south and north shores of the island.

Traversing structurally upwards toward the basement sliver along the southern shore of Sandsøya, the Altevik sequence is composed of calcite-bearing hornblende and biotite schist, biotite quartz-rich schist, amphibolite, clinozoisite-bearing ultramylonite, minor sulphide-bearing schist, quartzofeldspathic schist, and calcite marble.

The dominant rock type along the southern shore is a calcite-bearing hornblende-biotite schist. Outcrops of the rock type are observable along the shoreline and have an approximate combined thickness of 55 meters. The rock weathers from a gray to a dark-gray color and locally has a pitted appearance due to the dissolution of carbonate grains.

Along the northern shore of Sandsøya, the Altevik sequence is composed of amphibolite, calcite-biotite quartzofeldspathic schist, garnet-biotite quartz schist, and subordinate sulfide-bearing schist and quartzite. Amphibolite ranges in thickness from 5 to 20 m and commonly weathers grayish dark green to black in moderate- to well-banded samples. Garnet porphyroblasts (< 4 cm in diameter) are common in outcrop.

Basement Sliver. A strongly mylonitized coarse-grained granite gneiss lying structurally above the Altevik sequence is interpreted to be a sliver of Tysfjord granite gneiss of the basement complex. Structurally overlying the basement sliver is a flaggy quartzite assigned to the

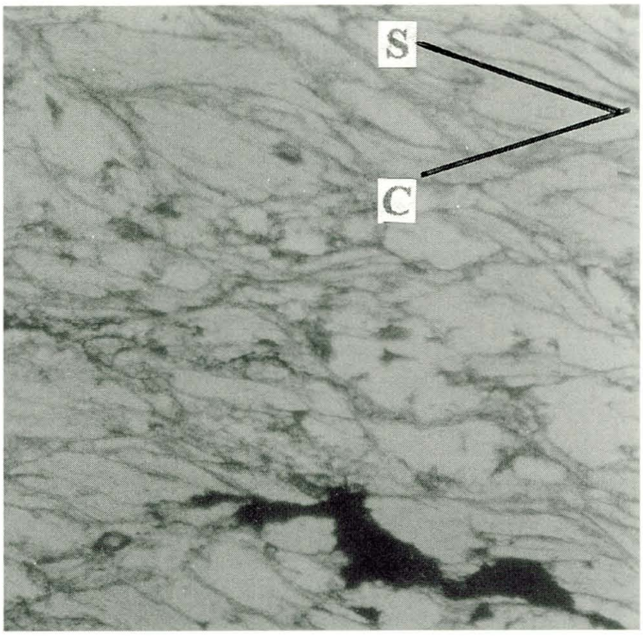

Fig. 7. Photomicrograph of S-C fabrics in granitic basement sliver. View in oriented thin-section is perpendicular to mylonitic foliation and parallel to the elongation lineation. Sense of shear is left-slip, top-to-the-northeast. Field of view is 0.2 mm.

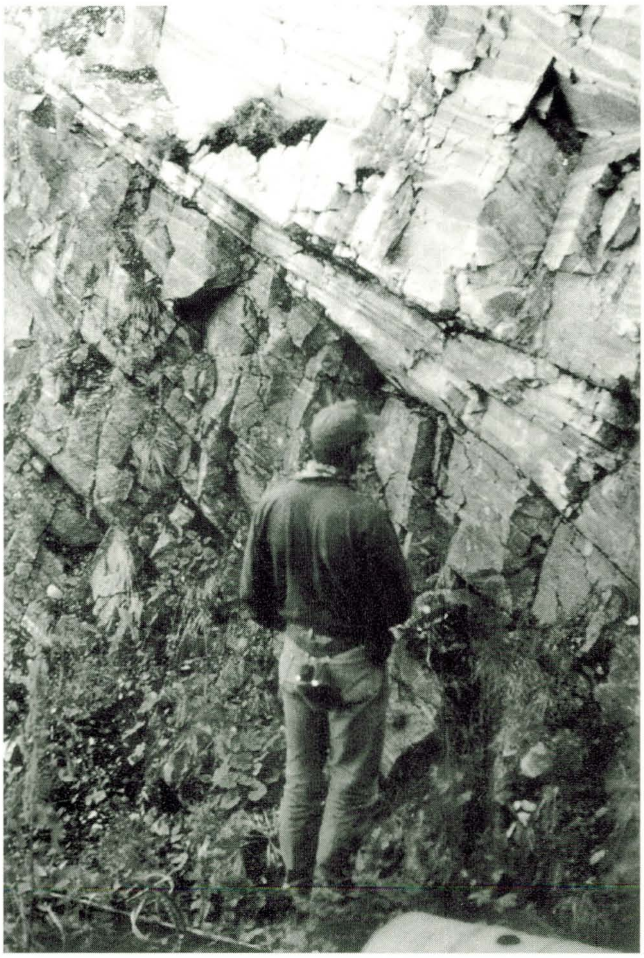

Fig. 8. Outcrop photograph of the contact between the granitic basement sliver (dark rock) and structurally overlying quartzite (light colored rock).

Kolsland schist sequence. This basement-cover contact can be traced nearly continuously along strike on the west flank of Vetten mountain (Fig. 2).

Rocks of the basement sliver range from a coarse-grained orthomylonite on northern Sandsøya to a fine-grained muscovite-bearing S-C granite mylonite on southern Sandsøya. Salmon pink microcline porphyroclasts are characteristic of the lower exposed portion of this unit but become less abundant structurally upward toward the upper contact. Locally, the basement sliver contains small (<8 m long) lenses of fine-grained actinolite-bearing biotite gneiss and epidote-biotite quartzofeldspathic gneiss that are interpreted to be mineralogical variations of the Tysfjord basement protoliths caused by mylonitic processes.

Orthomylonite is the most common rock type within the basement sliver. This rock ranges in thickness from 3 to 25 m and weathers from pinkish gray to medium gray in color. Pink microcline porphyroclasts (<3 cm in length) have extended tails of fine-grained recrystallized microcline that give the rock a banded mylonitic foliation. In hand sample, this rock is medium- to coarse-grained with survivor microcline porphyroclasts constituting 10% to 50% of the rock. In thin-section, this rock contains microcline, plagioclase, biotite, quartz, muscovite, epidote, and accessory calcite, clinozoisite, allanite, apatite, titanite, and opaques. Fine-grained muscovite-bearing S-C granite mylonite constitutes the uppermost 1 m of the basement sliver. This rock weathers gray to medium-gray in outcrop and contains microcline porphyroclasts (<2 cm in diameter). In thin-section the rock contains muscovite, microcline, quartz and plagioclase. The backs of muscovite 'fish' define the S-surfaces with extended tails of muscovite and microcline defining C-surfaces (Fig. 7).

Vetten schist sequence. The Vetten schist sequence lies structurally above the basement sliver on Sandsøya and below the Slagstad amphibolite (Fig. 2). The dominant rocks types include fine-grained flaggy quartzite, garnet-bearing biotite-muscovite-quartz schist, kyanite-garnet-biotite-muscovite schist, and garnet-quartzofeldspathic schist. Relatively less abundant are distinctive carbonate-bearing quartz schist, calcite and dolomite marble, feldspathic quartzite, and rare garnet-biotite amphibolite.

Well-foliated flaggy quartzite is in direct contact with the structural upper contact of the basement sliver on Sandsøya (Fig. 8). In outcrop the quartzite ranges in thickness from 1 to 15 m and locally is tan to buff colored with alternating dark-gray bands that are 1 to 20 cm thick. These bands are commonly faulted and folded. The quartzite readily breaks along micaceous parting planes into slabs 2 to 10 cm thick. Diffuse veins, <10 cm thick, of lighter colored quartz are common.

Above the basal quartzite is approximately 50 m of interbedded carbonate-bearing quartz schist, calcite and dolomite marble, feldspathic quartzite, and rare garnet-biotite amphibolite. These rocks crop out on the north and south ends of Sandsøya but were not traceable along strike toward the center of the island. The marbles in this sequence are distinct from other marbles on Sandsøya in that they are more micaceous, and contain large muscovite 'fish' (2-4 cm long). With the exception of the marbles, the remaining units are lithologically identical to those described for the Sørsand schist sequence and therefore will not be further discussed.

Structurally above these units is a 75 m thick garnet-muscovite-quartz schist. This schist forms the spine of Vetten mountain and is the most extensive unit structurally above the basement sliver. In outcrop, this rock weathers to a medium-gray to blue-gray color. Small (<2 mm diameter) garnets are visible on weathered surfaces. Hand samples are medium-grained and contain phacoid-shaped lenses of muscovite up to 2 cm long.

Structurally overlying the garnet-muscovite-quartz schist is approximately 75 m of kyanite-bearing garnet-biotite-muscovite phyllonite. This rock has a 'flaser' appearance and commonly weathers to a blue-gray color. In thin-section kyanite porphyroblasts (<3 mm long) are enclosed within muscovite lenses.

Slagstad amphibolite. The Slagstad amphibolite is a thick amphibolite unit above the 'flaser' schist and below the Kolsland marble and schist sequence on Sandsøya and Grytøya. It has a structural thickness of about 150 m on the northeast end of Sandsøya but thins southwestward to approximately 10 m on Grytøya. The banded amphibolite locally is interlayered with garnet amphibolite, hornblende-quartzofeldspathic schist and gneiss, and minor quartzite and marble. Outcrops of the amphibolite are distinctly foliated, weather dark-gray to black, and are locally crenulated. In thin-section the rock contains hornblende (40%), plagioclase (25%), biotite (15%), calcite (10%), quartz (5%), epidote (3%), and accessory chlorite, clinozoisite, titanite, and opaques.

The Kolsland marble and schist sequence. The Kolsland marble and schist sequence lies structurally above the Slagstad amphibolite and contains the highest units exposed on Sandsøya (Fig. 2). This sequence of rocks is greater than 300 m thick and consists of interleaved calcite and dolomite marbles, dolomite schist, various garnet-bearing two-mica schists, and subordinate quartzite and amphibolite. Rocks within this sequence are lithologically identical to those described for the Hallevika marble and schist sequence.

Åkerøya schist and marble sequence. An estimated 3500 m of the overlying lithologic section is under water between Sandsøya and Åkerøya. Detailed mapping on Åkerøya reveals eight major lithologic types that are here informally called the Åkerøya schist and marble sequence. The entire package of rocks is approximately 1200 m across strike and consists of alternating garnet-mica schist and calcite marble units. Other less abundant units observed in outcrop include amphibolite, garnet-bearing amphibolite, 'garbenschiefer', garnet-bearing gneiss, and carbonate-bearing amphibolite gneiss. The garnet-bearing amphibolite occurs as both sills and dikes that locally are enveloped and folded in the garnet-mica schist units.

The garnet two-mica schists range from 10 m to 200 m in thickness. Good exposures of these rocks are on the northwest side of the island. These units weather light gray to silver and characteristically contain abundant garnet (< 2 mm in diameter). Locally, the schist units contain a crenulation cleavage that overprints the earlier-formed schistosity. Minor staurolite and kyanite occur in the two structurally highest schists along the northern and southeastern shores of Åkerøya (Fig. 2).

The four calcite marble units range in thickness from 20 to 75 m. The three structurally lowest marble units are moderately banded, fine- to medium-grained, and weather dark gray to blue-gray in color. Outcrops of these lower units commonly have a blocky appearance and generally split along micaceous partings into layers less than 15 cm thick. The structurally lowest marble unit on Åkerøya contains thin discontinuous layers (<5 cm thick) of pink marble. The structurally highest marble unit in the sequence differs from the lower three units in that it contains less calcite and more mica and quartz, and does not readily break into slabs. In thin-section calcite grains (<2 mm across) make up approximately 90% of the mode and may be elongated with abundant deformation twins.

Kjøtta quartzite. Between the islands of Åkerøya and Kjøttakalven, approximately 300 m of the lithologic section is below water. A distinctive banded quartzite unit, herein called the Kjøtta quartzite, crops out along the west and northwest shores of Kjøtta and Kjøttakalven, respectively (Fig. 2). The minimum thickness of this unit, as measured where exposed above water, averages 40 m and forms a resistant ridge that is traceable along the entire length of the two islands. The quartzite has a distinct flaggy appearance, weathers tan to buff colored, and has a rusty-brown staining on some exposed surfaces. On Kjøtta this unit contains rare, thin, discontinuous sill-like bodies of amphibolite and thin layers of garnet-bearing two-mica schist, both of which are less than 0.5 m thick. In hand sample the rock is medium-grained and well-foliated with the dominant foliation being defined by micaceous partings less than 3 mm thick. Garnets up to 5 mm in diameter occur in the micaceous parting planes. In thin-section the rock has a equigranular texture with up to 90% quartz, garnet, muscovite, and accessory biotite, chlorite, calcite, plagioclase, epidote, apatite, hornblende, tourmaline, and opaques.

Cravslett schist sequence. The Cravslett schist sequence lies structurally above the Kjøtta quartzite on Kjøtta and Kjøttakalven (Fig. 2). It has a structural thickness of about 300 m but thins to approximately 75 m on southwest Kjøtta. Four different schist units have been recognized in this sequence. Traversing structurally upwards, these include a kyanite-staurolite-bearing garnet two-mica schist, staurolite-bearing garnet two-mica schist with thin quartz ribbons, hornblende-bearing garnet-biotite schist, and carbonate-bearing garnet two-mica schist. In outcrop the schist units weather from silver-gray to dark gray in color and commonly have a red-brown staining on exposed surfaces. Minor amounts of kyanite (<1%), and staurolite (<2%) occur in the lowest schist unit on Kjøttakalven.

Thin slivers of banded quartzite, less than 20 m thick, interlayered within the schist are lithologically indistinguishable from the Kjøtta quartzite (Fig. 2). Rare discontinuous bands of amphibolite and calcite marble (<1 m thick) in this sequence are commonly boudinaged.

Rodmelåsen marble and amphibolite sequence. The Rodmelåsen sequence lies structurally above the Cravslett schist sequence (Fig. 2). It has a structural thickness of about 100 m on the northeast end of the island but thins to approximately 25 m on the southwest shore. Rock types include interlayered gray to cream colored calcite marble and well foliated to massive, banded black amphibolite. In outcrop the marbles weather to a dull-gray to blue-gray color and commonly contain dimensionally aligned mica scattered throughout. On the southwest side of the island marble outcrops commonly contain small (<10 cm) vug-like pockets of epidote and clinozoisite.

Sandvika garnet two-mica schist. The Sandvika schist lies structurally above the Rodmelåsen sequence and has a structural thickness of approximately 100 m (Fig. 2). The unit generally weathers silver-gray to dark gray color. Overall the unit is very similar in mineral composition and appearance to schist units of the Cravslett mica schist sequence described above. In thin-section the only discernible differences between these rock types are the recognition of myrmekitic intergrowths of plagioclase and quartz and the common occurrence of microcline feldspar.

Kobbevika gneiss. The Kobbevika gneiss is the structurally highest rock exposed in the study area and is distinctive because it is the only intrusive rock, other than the basement sliver, found in the cover allochthons. It has a minimal structural thickness of approximately 10 m along the southeast shore of Kjøtta but the top is not exposed. The gneiss contains abundant felsic and mafic-rich pods, or lenses, (<25 cm in length) that parallel the dominant gneissosity and make up approximately 30% of the total volume of this unit. In thin-section the mafic pods contain predominantly hornblende (55%) and biotite (30%) with minor amounts of plagioclase, epidote, and quartz. The felsic-rich pods contain quartz (40%), plagioclase (30%), microcline (15%), and accessory epidote and sericitic mica. These pods become smaller in size and less abundant to the southwest. In outcrop the Kobbevika gneiss is medium- to coarse-grained and has alternating light and dark colored bands (<5 cm thick) defining the gneissosity. In thin-section the Kobbevika gneiss contains hornblende (20%), microcline (20%), plagioclase (oligoclase; 20%), biotite (15%), and quartz (10%). Microcline porphyroclasts have tartan twins and commonly are surrounded by myremekitic intergrowths of plagioclase and quartz.

Lithotectonic correlations

Figure 9 illustrates our interpretation of how rocks from the present study area correlate with similar units south of the study area on Hinnøy and with similar rock types throughout the Ofoten region. The structurally lowest exposed units in the study area, the granite and granitic gneiss of the Basement complex, are identical in appearance and composition to the Tysfjord granite and granite gneiss of the Western Gneiss Region, which has been described in detail by Gustavson (1966) and Andresen & Tull (1986). The older plutonic rocks are similar to lithologies reported in the younger plutonic sequence of Hames (1988) on Senja, north of the study area. On both Sandsøya and Senja metagabbro xenoliths are enclosed in large (>25 m^2), irregularly shaped bodies of metagranodiorite.

Metavolcanic and metasedimentary rocks of the Kråkeneset sequence can be roughly correlated with rocks of similar composition in the basement on eastern Hinnøy (Gustavson 1966, Bartley 1981a, Hakkinen 1977), and on Senja (Hames 1988). Hornfelses in the Kråkeneset sequence are similar in texture and appearance to hornfelses on Hinnøy described by Bartley (1981a). Hornfelses in both areas contain thin lenses of foliated amphibolite. Bartley suggested these amphibolite lenses represent sheared sections of the hornfelses. Other amphibolites occur as discontinuous lenses throughout the Kråkeneset sequence, a style that has been recognized in the younger plutonic sequence on Senja by Hames (1988). The remaining rock types of the Kråkeneset sequence, quartzite, schist, phyllonite, amphibolite, and marble are similar in composition to the Hesjevann assemblage of Bartley (1981a) and an unnamed sequence mapped by Hakkinen (1977) in the basement on eastern Hinnøy.

The Sørsand schist sequence overlying the basement gneiss comprises basal orthoquartzite, phyllonitic flaser schist, biotite-quartzofeldspathic schist, quartz-rich schist, feldspathic quartzite, and meta-arkose. The same lithologies occur within the Vetten schist sequence above the basement sliver, although the Vetten sequence contains micaceous calcitic and dolomitic marble. The Sørsand and Vetten schist sequences are assigned to the

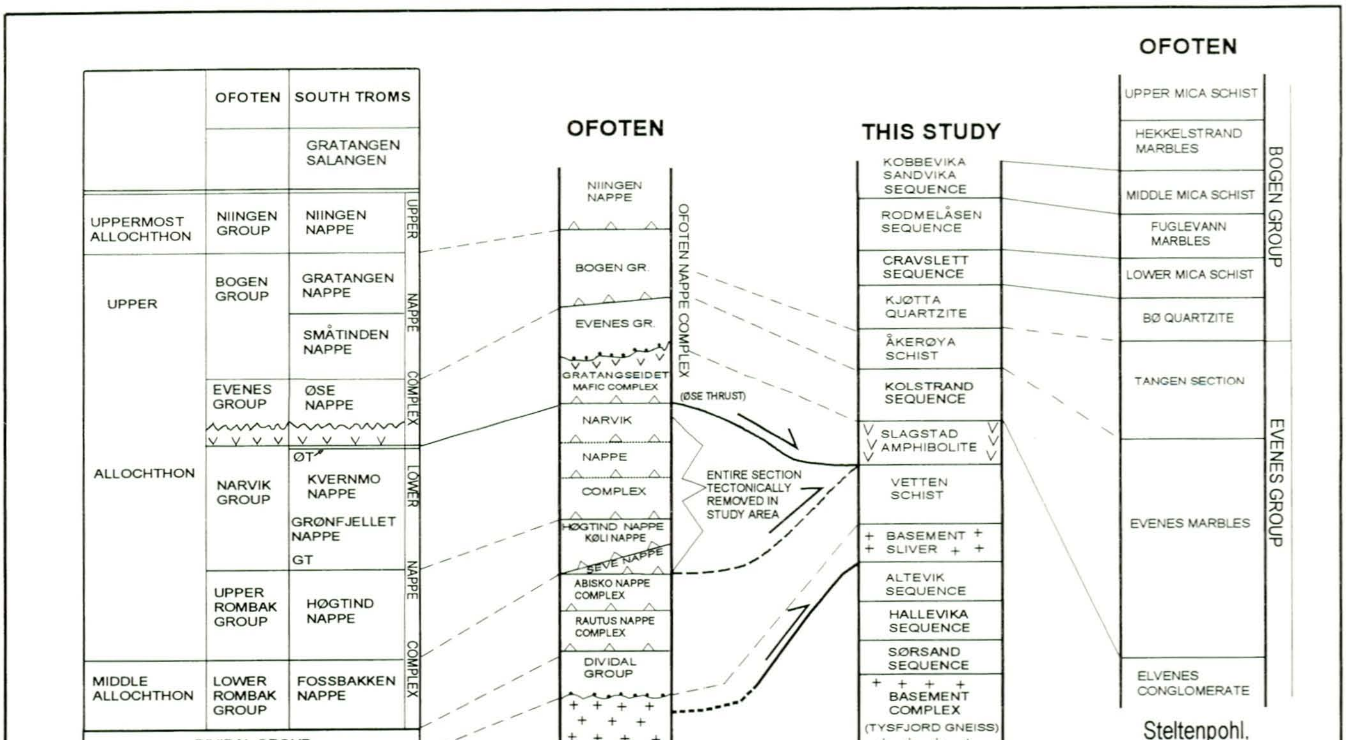

Fig. 9. Simplified columnar sections through the Ofoten and south Troms regions. Not to scale.

Lower/Middle Allochthon on the basis of their association with the underlying Precambrian basement and their lithologic make-up. The orthoquartzite at the bases of these sequences is similar to that overlying granitic basement of the Lower Rombak Group in the Harstad-Tjeldsund area (Gustavson 1966, 1972). Bartley (1981a, 1984) referred to these rocks as part of his Storvann Group on east Hinnøy. Björklund (1987) reported comparable units (sub-units A, E-I) overlying the basement in the Storvatn-Gausvik area on eastern Hinnøy. The overlying phyllonitic schist, flaser schist, biotite-quartzofeldspathic schist, quartz-rich schist, and feldspathic quartzite of the study area correspond to the mica schist and feldspar-bearing quartz schist of the Rombak Group (Gustavson 1966, 1972), to the mica schist of the Lower-Middle Complex (sub-units E, F, H) of Björklund (1987) and to the phyllonites and mica schists of the Fossbakken Nappe (Rombak Nappe Complex) described by Barker (1986) along the east limb of the Ofoten Synform. The feldspathic quartzite is strikingly similar to the 'hard schist', a strongly banded quartz schist, described by Gustavson (1966) in the Storfjell and Rombak Groups and of the Abisko Nappe in the Swedish foreland (Bax 1989). The meta-arkose in this sequence is lithologically identical to the feldspathic schist (sparagmite schist) of the Storfjell Group (Gustavson 1966), which corresponds to the distinctive sparagmite schists of the Lower and Middle Allochthons in Sweden (Bax 1989). The thin lenses of quartzite, and dolomite and calcite marble interleaved with the above units are reported to be typical of the Storfjell Group (Gustavson 1966).

The Hallevika and Kolsland marble and schist sequences, which structurally overlie the Sørsand and Vetten schist sequences, are characterized by thick, clean and banded dolomite and calcite marble interlayered with thin garnet two-mica schist. These marble sequences are interpreted to correspond to the Evenes Group of the Upper Allochthon's Ofoten Nappe Complex (Gustavson 1966, Andresen & Steltenpohl 1991, 1994) on the basis of lithology and tectonostratigraphic position and because they project in to and can be traced directly into the type units to the south of the study area. Barker (1986) described a similar, carbonate-rich sequence at the same structural level in the Høgtind Nappe of the Rombak Complex on the east limb of the Ofoten Synform. The base of the Evenes Group typically is marked by the Elvenes or Harstad conglomerates (Gustavson 1966, Steltenpohl et al. 1990) which have a nonconformable contact with underlying mafic complexes that Andresen & Steltenpohl (1991, 1994) correlated with the Lillevik dike complex (Boyd 1983) and Lyngen Ophilitic Complex (Minsaas & Sturt 1985). The bases of the Hallevika and Kolsland sequences are marked by amphibolites which we correlate with similar amphibolites below the Harstad conglomerate on Hinnøy (Gustavson 1974, Bartley 1984) and the above-mentioned mafic complexes at the base of the Ofoten Nappe Complex (Andresen & Steltenpohl 1991, 1994). The fault at the base of the Ofoten Nappe Complex (i.e., the Øse thrust of Barker 1986 and Andersen et. al. 1992) has apparently removed the entire Narvik Nappe Complex and the Høgtind Nappe in the study area.

Correlation of the overlying Altevik sequence is difficult due to the chaotic distribution and relatively thin and discontinuous nature of lithologies. We suggest its correlation with part of the Bogen Group of the Ofoten Nappe Complex (Andresen & Steltenpohl 1991, 1994) based on tectonostratigraphic position and the abundance of schist interlayered with relatively thin calcitic marbles and feldspathic quartzite units. The thin sliver of basement structurally overlying the Altevik sequence on Sandsøya and Grytøya corresponds to imbricated basement gneiss of the Middle Allochthon of Gustavson (1966), Björklund (1987), and Andresen & Rykkelid (1991).

The calcite marbles, garnet-bearing two-mica schist, and garbenschiefer of the Åkerøya marble and schist sequence clearly correspond to units of the Tangen sequence of the Evenes Group reported by Steltenpohl et al. (1990), on the basis of tectonostratigraphic position above the thick, clean marble sequences and below the Kjøtta quartzite, the latter of which clearly is equivalent to the Bø quartzite of the Bogen Group (Gustavson 1966, Steltenpohl et al. 1990). Other similarities with the Tangen sequence are thin layers of amphibolite and garnet-bearing amphibolite, which occur as thin concordant layers enveloped between the mica schist units and thin discontinuous quartzites that are commonly boudinaged (Steltenpohl et al. 1990).

The remaining, structurally higher units of the study area are interpreted to correlate with lithologies of the Bogen Group (Gustavson 1966, Steltenpohl et al. 1990). The Kjøtta/Bø quartzite is an especially important correlation tool and provides further continuity to this distinctive regional marker unit (Gustavson 1972, Steltenpohl et al. 1990). Garnet two-mica schist of the overlying Cravslett schist sequence corresponds to the lower mica schist of Steltenpohl et al. (1990). The Rodmelåsen marble and amphibolite sequence corresponds to the Fuglevann marble of Gustavson (1966) and Steltenpohl et al. (1990) on the basis of lithologic similarities and stratigraphic position. The overlying Sandvika garnet two-mica schist is interpreted to correspond to the middle mica schist of Steltenpohl et al. (1990) and the Kobbevika gneiss is similar to units containing felsic and mafic injections and lenses within the Middle mica schist (Steltenpohl 1983, 1987).

Structural Geology

Rocks of the study area record at least four episodes of deformation. Detailed structural and petrographic analyses indicate that these events can be broadly grouped into two early-phase amphibolite-facies events, D_1 and D_2, followed by two post-metamorphic peak events, D_3 and D_4, that occurred under retrograde, greenschist-facies conditions. Early-phase deformations are interpreted to be associated with nappe emplacement whereas late-phase deformations produced ductile shear zones in the basement complex and folds in the allochthonous cover units. Structural notation used indicates that the structures and fabrics resulting from a particular deformational event are numbered the same as that event; for example L_1, S_1, and F_1 formed during D_1 and L_2, S_2, and F_2 formed during D_2, and so on.

D_1 Deformation

Evidence for the earliest deformational event recognized in rocks of the study area, D_1, is limited due to intense overprinting during the later, kyanite-grade, D_2 event. However, mesoscopic and microscopic evidence for D_1 is found in each of the Caledonian allochthons of the study area.

Folds. Isoclinal F_1 fold hinges in quartzite that fold compositional layering S_0 have an axial planar metamorphic foliation S_1. F_1 folds and their S_1 fabrics are refolded by tight, shallow northeast-plunging F_2 folds that contain an axial planar foliation, S_2, which is the dominant schistosity in rocks of the study area. A result is the general parallelism of the S_0/S_1 foliation and S_2, referred to below as the S_1/S_2 foliation.

Fabrics. Petrographic evidence for D_1 deformation is rare and limited to inclusion trails in garnet and staurolite poikiloblasts. S_i in the poikiloblasts is commonly folded or snowballed and is discordant with the surrounding S_e foliation, S_2, which is defined by the peak metamorphic mineral assemblages.

Fig. 10. Outcrop photograph of tight F_2 folds in quartzite along basement-cover contact.

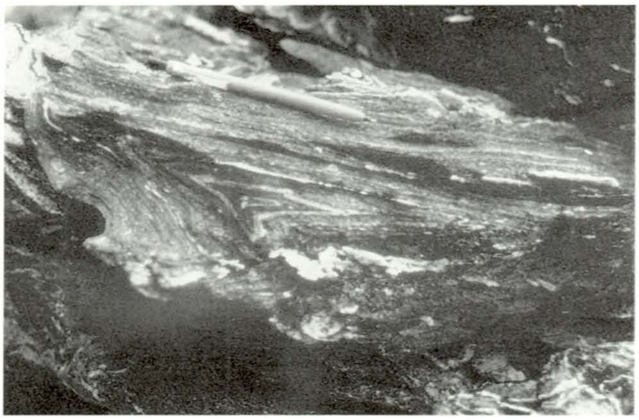

Fig. 11. Outcrop photograph of refolded F_2 fold in amphibolite at the base of the Hallevika schist and marble sequence exhibiting a Ramsay Type II interference pattern between F_2 and F_3 folds.

D2 Deformation

D_2 was the most pervasive structural and fabric-forming event recognized in rocks of the study area. Prograde metamorphism during this event developed peak, lower to middle amphibolite-facies (kyanite and staurolite grade) mineral assemblages.

Folds. F_2 folds are common to practically all rock types. They are tight folds in quartzite (Fig. 10) and marble with thickened hinges and thinned limbs. F_2 folds and their axial-planar S_2 fabric are refolded by F_3 folds resulting in Ramsay (1967) type II (Fig. 11) and III interference patterns. F_2 folds typically have amplitudes that range up to several meters.

Fabrics. Two main fabric elements were produced during D_2, the dominant S_2 schistosity and various types of L_2 lineations. S_2 is defined by lower to middle amphibolite-facies, kyanite- and staurolite-grade assemblages. The S_2 foliation parallels the basement-cover contact and the thrust boundaries between the allochthons. S_2 is traceable structurally downward for approximately 50 to 100 m beneath the basement-cover contact into the Tysfjord granite gneiss but gradually disappears, a relation recognized regionally along the Western Gneiss Region basement-cover contact (Tull 1972, Bartley 1981a, Hodges et al. 1982). Stereographic projections of S_2 indicate gentle dips to the southeast which become sub-horizontal toward the southeast (Fig. 12), indicating the structural position of these units along the western limb of the regional Ofoten synform; partial p-girdles defined by the S_2 poles in figure 12 reflect late-phase folding, discussed below. A pronounced L_2 stretching lineation lies in S_2 and plunges gently to the east-southeast (Fig. 13), generally corresponding to L_2 lineations found regionally along the western limb of the Ofoten synform (Steltenpohl 1987). The L_2 lineation is interpreted to record the D_2 transport direction along which the

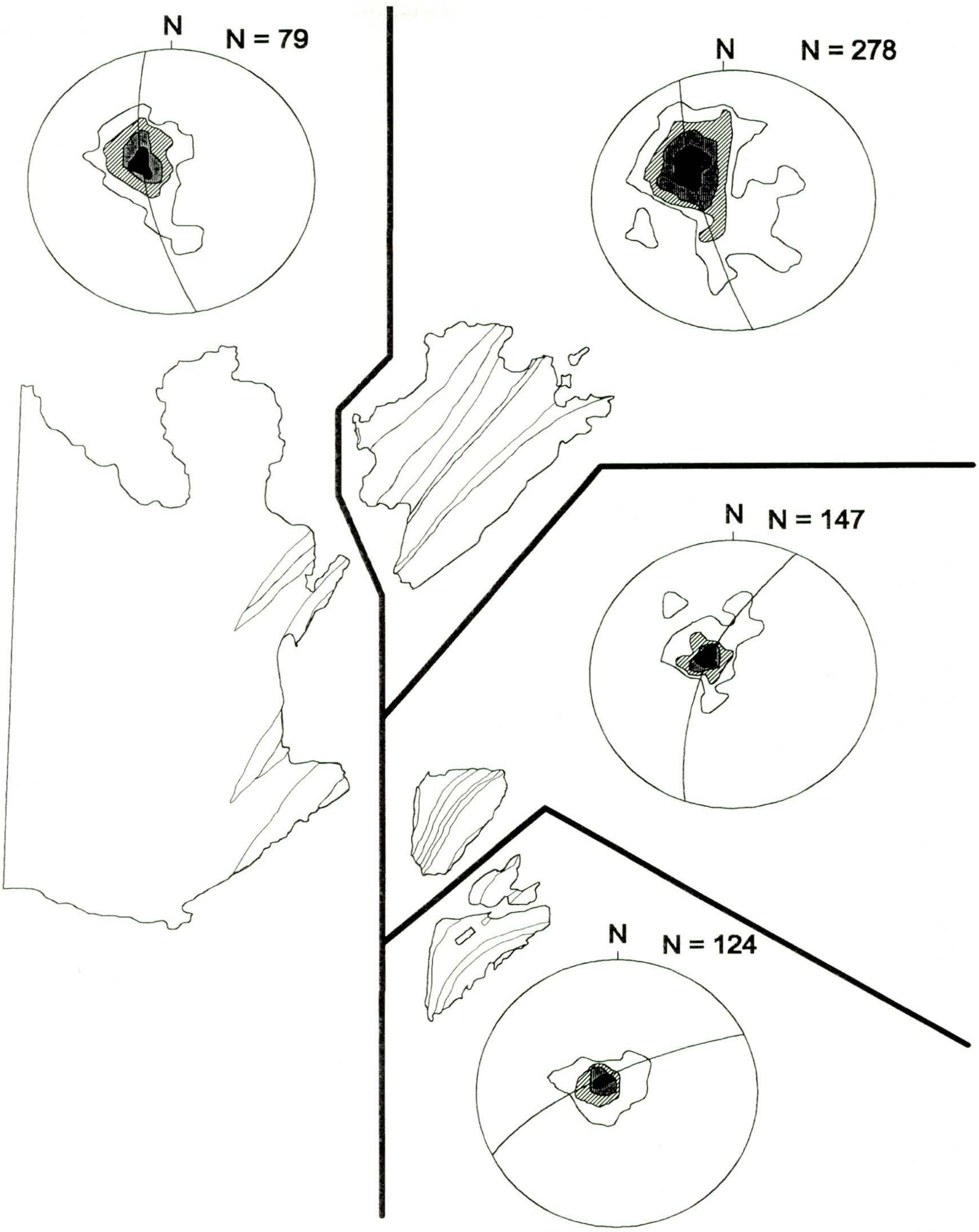

Fig. 12. Contoured lower hemisphere stereographic projections of poles to S_1/S_2. Contours are Sandsøya 4% - 14% - 17% - 22%; Grytøya 2% - 4% - 15% - 30%; Åkerøya 8% - 25% - 39% - 74%; Kjøtta 11% - 31% - 47% - 97% per 1% area.

Caledonian nappes were emplaced (Steltenpohl 1987).

Thrusts. All thrusts in the study area are interpreted to be D_2 structures based on parallelism of D_2 fabrics and structures across the faults, the lack of detectable metamorphic grade differences across them and because fabrics and mineral assemblages observed in the thrusts are compatible with having formed under D_2 deformational conditions. However, only two thrust boundaries, that at the base and one at the top of the basement sliver, were directly observed. The other thrusts are inferred based on lithologic contrasts across the boundaries and regional lithologic similarities with known thrust-bounded nappes.

The contact between the Tysfjord granite gneiss of the Basement complex and overlying cover rocks of the Sørsand schist on Sandsøya is interpreted as a thrust (Fig. 2). Evidence to support this is the strong S_2 foliation and

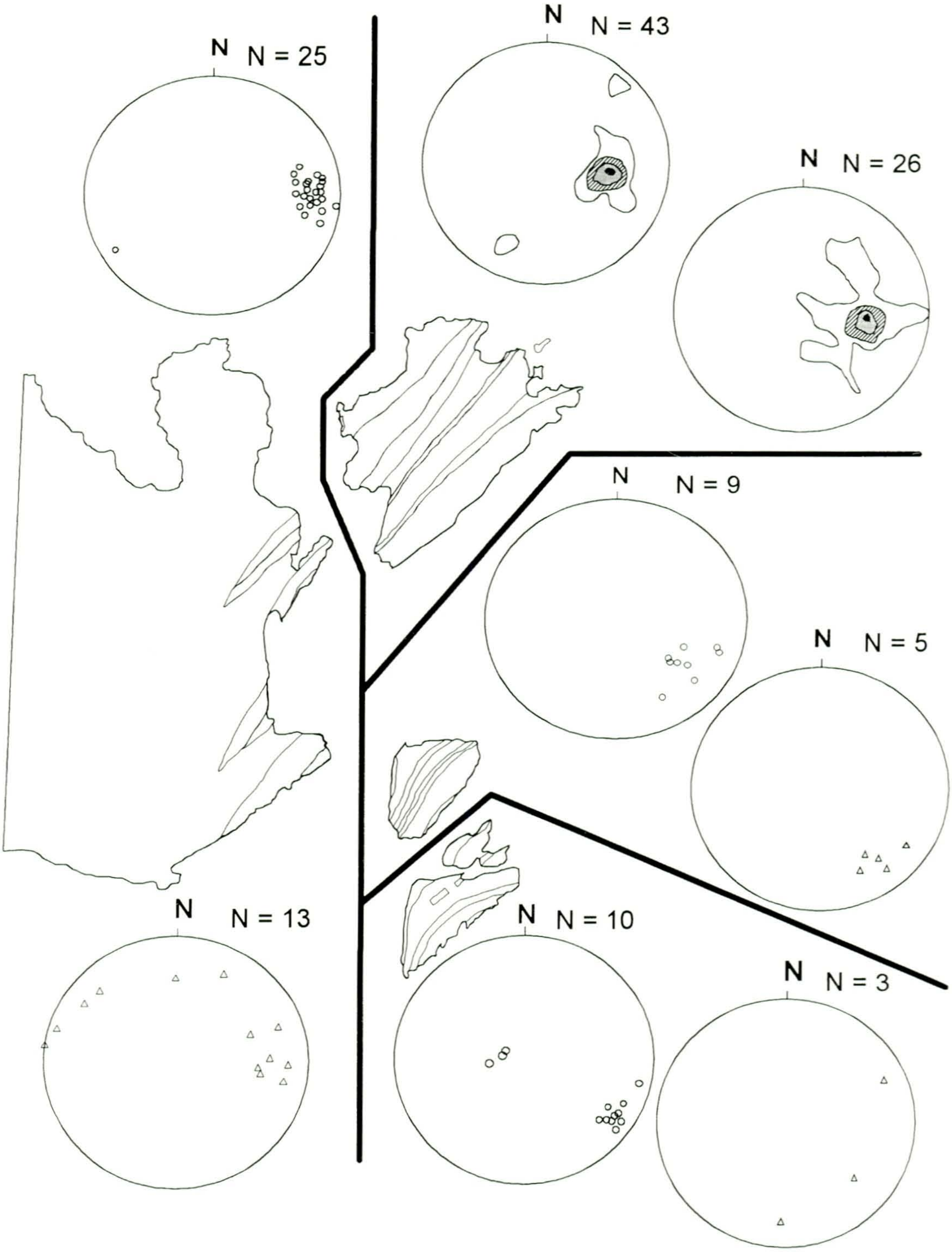

Fig. 13. Lower hemisphere stereographic projections of syn-and post-metamorphic stretching lineations. Contours for Sandsøya (post-metamorphic, n = 43) 1% - 3% - 5% - 7%per 1% area; (syn-metamorphic, n = 26) 1% - 3% - 5% - 7% per 1% area; Circles = post-metamorphic. Triangles = syn-metamorphic.

associated L_2 mineral elongation lineation that is progressively developed within basement granite as the basement-cover contact is approached and which parallels fabrics in the overlying cover units. Amphibolite-facies mineral assemblages defining S_2 in basement and cover units and the lack of a retrogressive deformation zone indicate that this boundary probably is a syn-M_2 thrust.

Thrusts are interpreted to lie between the Sørsand and Vetten schist sequences and between the Hallevika and Kølsland marble and schist sequences. The amphibolite at the base of the Hallevika sequence is in the same tectonostratigraphic position beneath the Evenes Group and

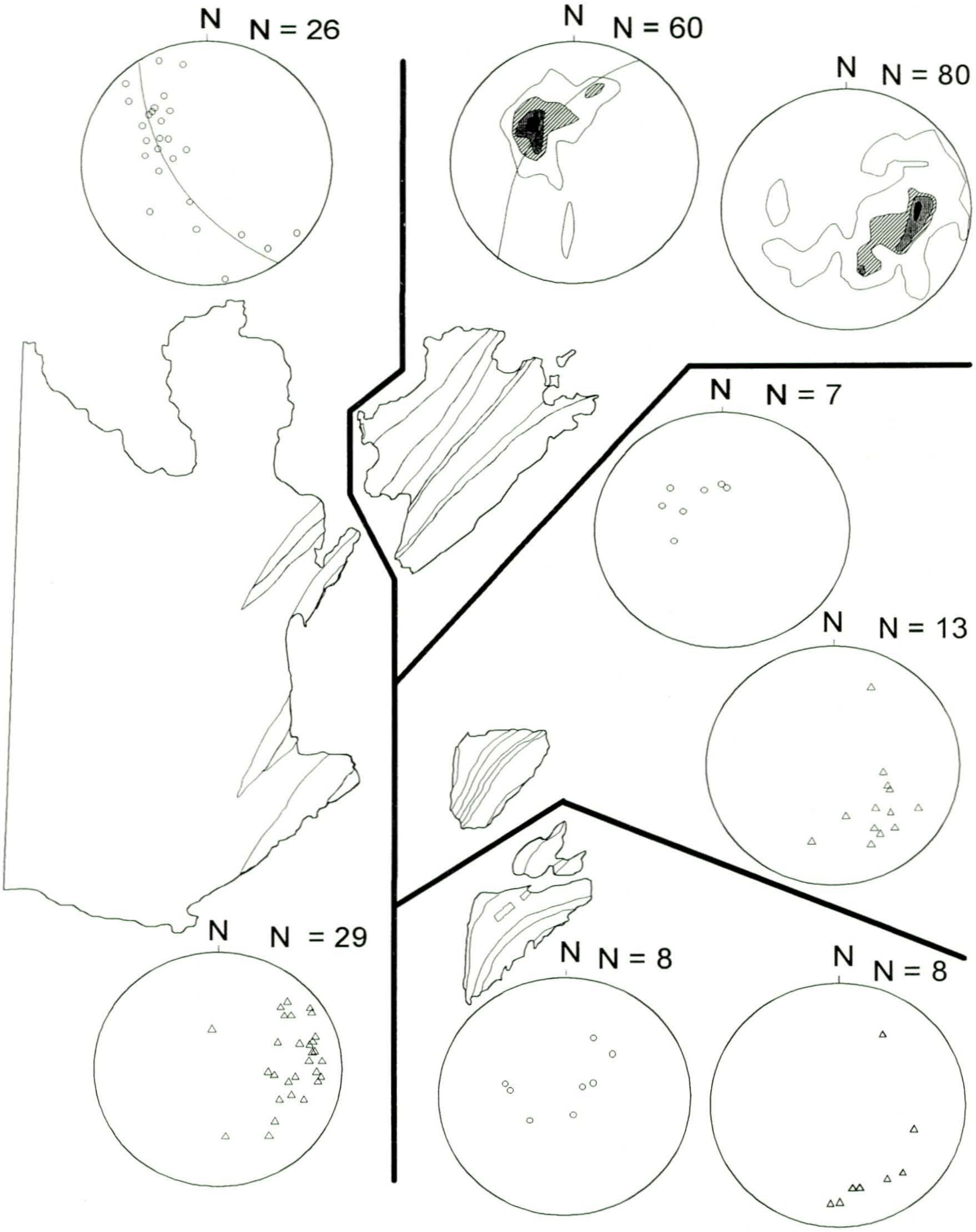

Fig. 14. Lower hemisphere stereographic projections of F_3 and F_4 fold axes (open triangles or lower contoured diagram [4%, 14%, 17%, 22% per 1% area]) and poles to axial surfaces (open circles or upper contoured diagram [3%, 13%,16%, 21% per 1% area])for illustrated subareas.

the ophiolite fragments throughout the Ofoten-Troms region (Andresen & Steltenpohl 1994). Because oceanic crust is involved, this contact marks a potentially important tectonic boundary within the Upper Allochthon.

The contact between the basement granite sliver and the underlying Altevik sequence is interpreted to be a thrust (Fig. 2). The lower contact of the granite sliver is marked by an intensified mylonitic foliation and migmatitic gneiss. The mylonitic foliation is defined by amphibolite-facies mineral assemblages and these fabrics and assemblages continue both structurally above and below the contact, implying that the granite sliver was thrust upon the Altevik sequence during the thermal peak. The upper contact of the basement sliver is marked by flaggy quartzite. Structurally upward toward the quartzite, the granite becomes progressively finer grained due to higher degrees of dynamic recrystallization. This indicates dynamic rather than thermal intrusive effects for the formation of this boundary, which, coupled with relations observed in the foreland, lead us to suggest that this may be a nonconformity that was structurally modified during early-phase thrusting.

A thrust boundary has been inferred between the islands of Åkerøya and Kjøttakalven (Fig. 2). This boundary separates rocks correlative with the Evenes and Bogen Groups which is interpreted to be a regional thrust throughout western Ofoten (Steltenpohl et al. 1990). Observations supporting this interpretation are: (1) the Kjøtta quartzite is lithologically identical to the Bø quartzite; (2) the boundary marks a strong contrast between rock types; and (3) felsic intrusions, other than basement rocks, occur in units structurally above the Kjøtta quartzite but are absent in rocks below this contact.

Fig. 15. Ductile deformation zone within homogeneous Tysfjord granite. Note S-C fabrics (S is subhorizontal and C dips shallowly to the right in the photograph. View is parallel to the elongation lineation and perpendicular to the mylonitic foliation; top-to-the-northeast sense-of-shear looking northwest, slightly up the dip of the mylonitic foliation.

D_3 and D_4 Deformation

Late-phase D_3-D_4 structures and related fabrics deform and overprint all earlier structures. Rocks and related fabrics associated with these two events are interpreted to record the transition from amphibolite- to greenschist-facies conditions subsequent to but perhaps overlapping with the late stages of D_2 nappe emplacement.

Folds. Two distinct late-phase fold sets, F_3 and F_4, commonly are observed to have refolded F_2 folds. F_3 folds have gentle (<30°), east-southeast plunging axes and axial planes that dip shallowly to the southeast (Fig. 14). Where F_3 and F_2 folds are observed in the same outcrop, Ramsay type II (boomerang and canoe) fold interference patterns predominate. F_3 folds of the study area are correlative with regional F_3 cross-folds of Steltenpohl & Bartley (1988). The F_3 folds correspond to macroscopic F_2 folds of Gustavson (1972) and late-phase F_3 cross-folds of Bartley (1981a, 1984), Steltenpohl (1983, 1987), and Steltenpohl & Bartley (1988), and F_4 folds of Hodges (1985). Along the eastern limb of the Ofoten synfom, Barker (1986) and Barker & Anderson (1989) do not report folds corresponding to the present authors' F_3 and F_4 fold sets. Steltenpohl & Bartley (1988) suggested that these relations indicate that the F_3 and F_4 folds die out to the east across the hinge of the Ofoten synform.

F_4 folds have gently plunging, east- to northeast-trending axes with southeast-dipping axial planes (Fig. 14). Ramsay type III interference patterns (hooks) formed where F_4 folds deformed F_2 folds. F_4 fold axes parallel the orogenic trend but verge to the northwest in the opposite sense from that of nappe transport and thus are called back-folds (Steltenpohl & Bartley 1988). F_4 folds are of the same generation as the Ofoten synform (Steltenpohl & Bartley 1988).

Steltenpohl & Bartley (1988) described how the F_3 cross-folds and F_4 back-folds are difficult to separate in practically every regard except orientation and provide a detailed description and analysis. Results from the present study add no new information concerning these fold sets and are consistent with the observations reported by Steltenpohl & Bartley (1988). Minor folds related to these fold sets are characterized by the same range of fold styles and fabrics as a function of lithology. The descriptive

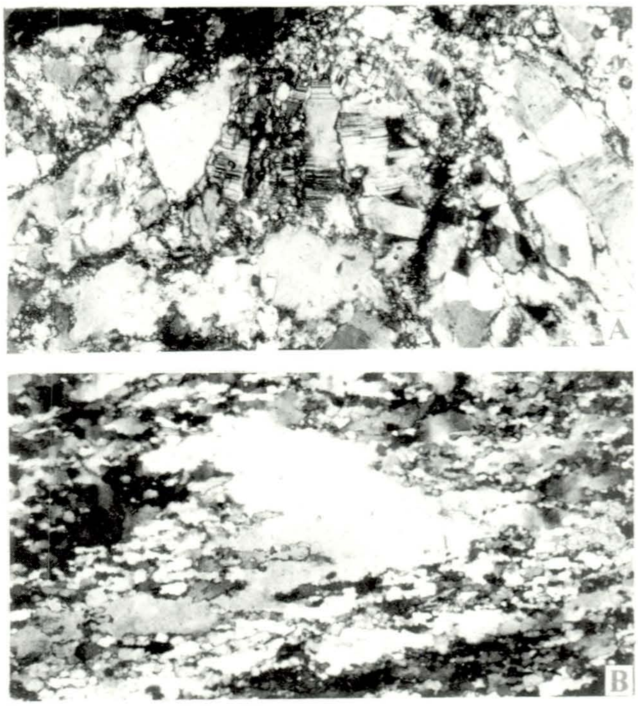

Fig. 16. Photomicrographs of greenschist-facies microstructures within mylonitized Tysfjord Granite of the basement complex. a) Fractured and displaced feldspar grains indicating crystal-brittle behavior of feldspar. b) Crystal-plastic behavior of quartz. Note quartz ribbons, LPO, grain boundary bulges and sub- and new-grain development indicating dynamic recrystallization. Field of view (horizontal) is 2 mm for both photomicrographs.

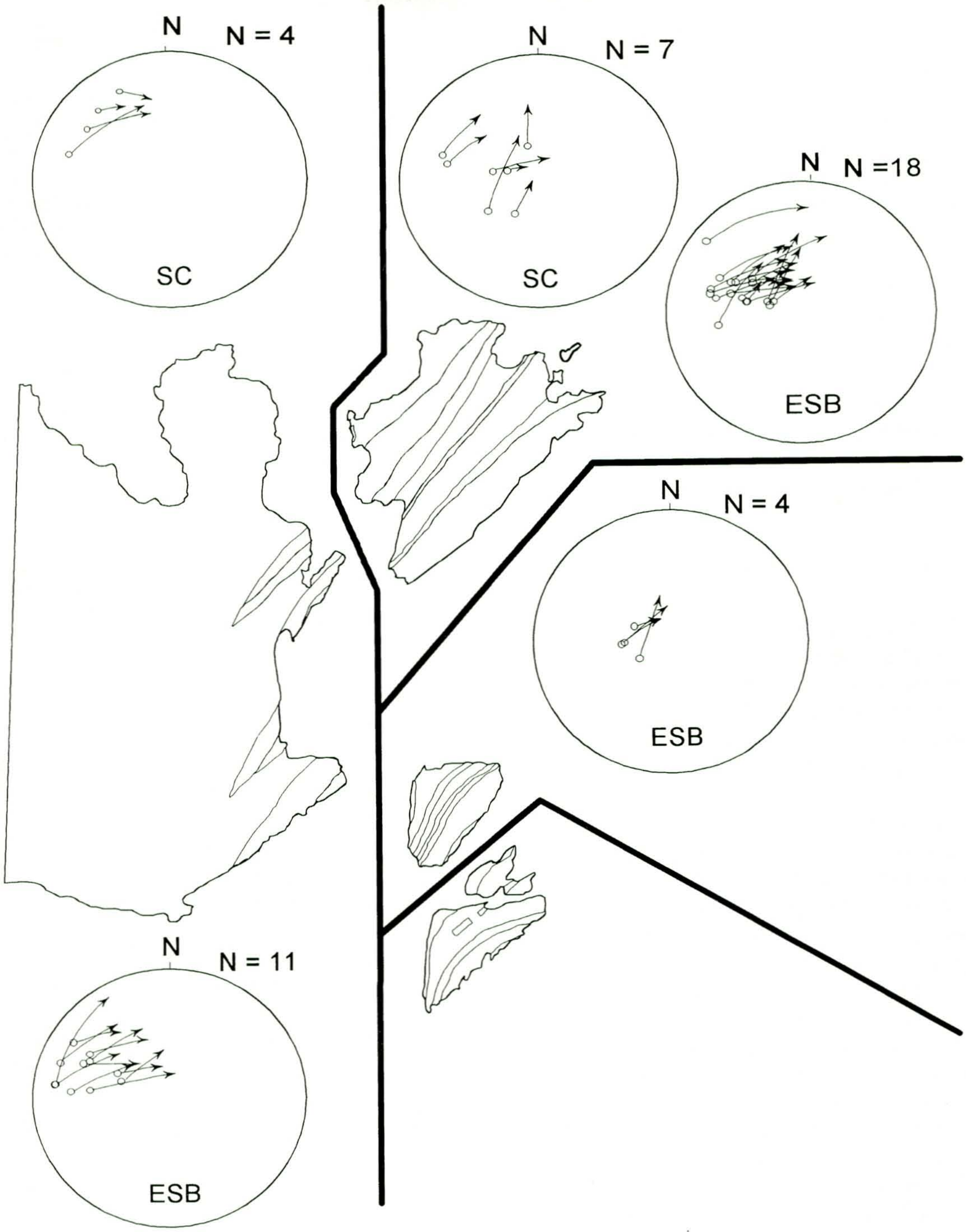

Fig. 17. Lower hemisphere stereographic projections of poles to S-C and S-extensional shear-band pairs. The poles to C-planes and shear bands (circles) are connected by their common great circle with the arrow tips indicating the locations of the S-surface poles and pointing in the direction of top movement. See text.

similarities between these fold sets imply that the back-folds and cross-folds formed very close in time at very similar crustal conditions and levels.

Fabrics. D_3 fabrics include an S_3 crenulation cleavage and related L_3 crenulation fold-hinge lineation that locally deforms S_2 in amphibolite and phyllonitic cover units. In some locations, S_3 is highly deformed by a D_4 related transposition cleavage, S_4. F_3 and F_4 folds locally have an axial-planar crenulation cleavage, S_3 and S_4, respectively, along which the earlier-formed amphibolite-facies mineral assemblage defining S_1/S_2 is retrograded to greenschist-facies assemblages. A weakly developed, subhorizontal, NE-SW-trending elongation lineation, defined by

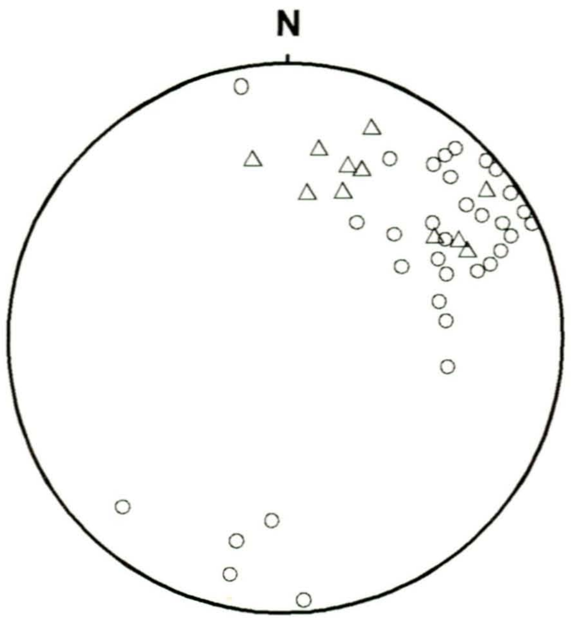

Fig. 18. Slip-lines determined from ductile shear zone fabrics in basement rocks (S-C, open triangles) and phyllonitic cover units (S-extensional shear bands, circles).

elongate microcline porphyroclasts and quartz ribbons, lies within the mylonitic foliation S_3 of ductile shear zones.

Shear zones. Late-phase ductile shear zones that affect the basement and cover units of the study area are interpreted as transitional D_2 through D_3 structures. These NE-SW-striking shear zones are typically less than 2 m thick and overprint D_1 and D_2 fabrics and structures. In the relatively isotropic basement units, the shear zones generally are anastomosing features randomly dispersed but concentrated near the basement-cover contact. The zones are concentrated along the boundaries of supracrustal enclaves, implying that the latter played a role in localizing strain, perhaps due to dewatering during metamorphism. Isotropic undeformed Tysfjord granite can be traced progressively into a strong mylonitic foliation within the shear zones (Fig. 15). In the center of some shear zones, epidote group minerals are concentrated, constituting up to 60% of the visual mode of the orthomylonite, imparting a distinct green coloration to the shear zone rocks.

Deformational mineral assemblages and microstructures of the basement shear zone orthomylonites indicate a transition from amphibolite-facies to greenschist-facies deformational conditions. The retrogressive mineral assemblage sphene + chlorite + biotite + epidote + quartz defines the mylonitic foliation of the shear zones and represents the higher temperature end of this transition. In these shear zones, crystal-plastic behavior of quartz and feldspar implies deformational temperatures of >450 °C (Simpson 1986). Mylonite samples of basement granite from shear zones referred to as `transitional' contain fractured feldspar microcline grains and abundant ribbon quartz (Fig. 16). Brittle feldspar and plastic quartz microstructures support that shearing in the transitional zones occurred between temperatures of approximately 450° and 300° C (Simpson 1986).

Kinematic analysis of the late-phase shear zones was performed on field exposures and oriented hand specimens and thin-sections viewed perpendicular to the mylonitic foliation and parallel to the elongation lineation. Porphyroclast systems, lattice and grain-shape preferred orientations (LPO and GSPO, respectively) in quartz, S-C composite planar fabrics, and extensional shear bands (ESB's) all document subhorizontal to shallow northeast, strike-parallel, left-slip transport along shallow southeast-dipping shear surfaces. Stereographic projections of S-C planes and S-ESB's connected along their common great circle indicate that displacement along the C and ESB surfaces was top toward the northeast (Fig. 17). Slip-lines, determined by taking the acute bisectrix of the intersection S-ESB planes (Dennis & Secor 1987), and S-C (Berthé et al. 1979), which lie in the C-plane, and projecting them 90 degrees along their common great circle in the direction of transport, cluster with gentle plunges in the northeast and southwest quadrants, consistent with strike-parallel directed movement (Fig. 18).

Phyllonitic zones within the structurally lower parts of the overlying allochthons parallel the shear zones in the basement and have the same top-to-the-northeast sense of displacement. The phyllonite zones that occur in schists structurally above the basement-cover contact on Sandsøya and Grytøya contain large 'buttons' of mica (<4 cm in length) (Fig. 6). Like the shear zones in the basement, these phyllonite zones clearly overprint and retrograde the earlier-formed amphibolite-facies mineral assemblages. In the case of the phyllonites, this assemblage is the kyanite-grade S_2 schistosity. Based on their similar orientations, kinematics and deformational conditions, we interpret the phyllonite zones to have formed simultaneously with ductile shearing in the basement. All of the shear zones are concentrated along and formed subparallel to D2 thrusts indicating reactivation of these previously formed structures.

Faults. A subvertical, NE-SW-trending breccia zone truncates the basement-cover contact on Grytøya and is interpreted to be a late-phase, high-angle, down-to-the-west fault. The fault cuts massive and mylonitized Tysfjord granite. Breccias containing clasts of mylonite are exposed along the shoreline. Potassium feldspar grains, ordinarily gray to milky colored, become a deep-salmon color as the breccia zone is approached and within the zone itself. Multiple generations of veins are commonplace. Purple fluorite crystals fill veins and occupy areas between the salmon-colored granite clasts. White calcite is also found as vein material and as part of the breccia matrix. Subvertical slickensided surfaces contain down-dip fibre lineations. Some quartz grains contain drusy quartz along their contacts documenting open-space filling. The breccia zone is similar to the late-stage faults described on neighboring Hinnøy (Bartley 1981a) and Skånland (Steltenpohl 1987). Other late-phase brittle faults recognized in the area deform units of the Upper Allochthon.

^{40}Ar/^{39}Ar Thermochronology

^{40}Ar/^{39}Ar isotopes of two hornblende and one muscovite sample were measured (Table 1) in M. Kunk's laboratory, USGS, Reston, Virginia, in an attempt to place constraints on the timing of cooling following the last thermal event affecting these rocks. Analytical techniques and a discussion of error estimates and closure temperatures are described elsewhere (Steltenpohl & Kunk 1993). Two hornblende samples (S-40 and S-45) came from an amphibolite at the base of the Evenes Group (Upper Allochthon) on Sandsøya (Fig. 2 for locations). Age spectra for the two hornblende separates have produced a 'saddle shaped' pattern (Fig. 19), suggestive of extraneous argon, which is a common problem in applying this technique to Norwegian rocks (Coker 1993, Coker et al. 1995). The minimum-age steps in the two profiles are 428 Ma and 421 Ma, respectively. ^{36}Ar/^{40}Ar versus ^{39}Ar/^{40}Ar correlation plots did not provide meaningful information on sample S-40. The disturbed spectrum has two saddle minimums separated by a hump that implies resetting from an earlier cooling through argon retention. For sample S-45, however, 8 points regressed out of 10, providing an apparent age of 408.7 +/- 5.3 Ma,(89.4% of ^{39}Ar, MSWD = 2.6, ^{40}Ar/^{39}Ar = 798.3 +/- 35), which is consistent with the minimum age of the saddle trough for both S-40 and S-45. Muscovite sample S-42 is from a garnet-muscovite-biotite schist from Middle Allochthon rocks on Sandsøya. This age spectrum is weakly diffusional, stepping up in age to ca. 401 Ma in the highest temperature step, which implies a partial resetting at and final closure at around 391 Ma (Fig. 19).

The ^{40}Ar/^{39}Ar data are interpreted as follows: the date on hornblende S-45 indicates cooling below 500° C at ca. 408 Ma following the kyanite-grade metamorphic peak, M_2. Muscovite sample S-42, from the same area, records subsequent cooling through approximately 350° C at about 391 Ma. Microstructural observations from mylonite samples of the basement shear zones indicate temperatures of deformation between about 450° C and 300° C, which is within the range of hornblende and muscovite closure temperatures. The 408 and 391 Ma dates on hornblende and muscovite are corroborated by ^{40}Ar/^{39}Ar dates for the same phases sampled throughout western Ofoten (Coker et al. 1995). Conventional K/Ar biotite cooling dates on biotite from basement and cover rocks from Ofoten range mainly between 360 and 370 Ma (see Steltenpohl & Bartley 1992). Combined, these dates constrain the formation of the late-phase shear zones to between about 408 Ma and 370 Ma.

Discussion

Results of our detailed lithologic mapping on Sandsøya and adjacent islands conflict with the earlier maps compiled for this area. Gustavson's (1966, 1972) maps assign all lithologies on these islands to the Lower/Middle Allochthons. A subsequent map by the same author (Gustavson 1974), shows the study area to contain only rocks of the basement and the Upper Allochthon. Our mapping documents that thin slivers of basement separate repeated Lower/Middle and Upper Allochthon sequences on Sandsøya and Grytøya. Allochthonous cover units on Åkerøya and Kjøtta are assigned to the Upper Allochthon.

Two main models have been developed for the evolution of the basement-cover contact in western Ofoten. Gustavson (1972) proposed a thin-skinned or 'dish model' for the formation of this boundary. The dish or thin-skinned model holds that the main Caledonian allochthon occupies a broad synclinorium between the two basement terrains (i.e. Rombak window and Western Gneiss Region) which are structurally continuous at

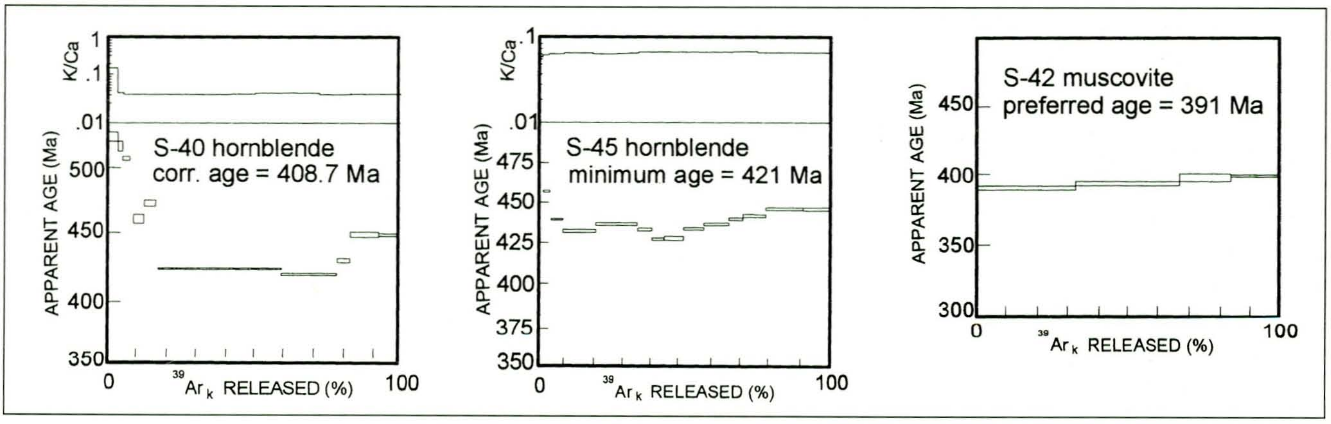

Fig. 19. ^{40}Ar/^{39}Ar age spectra for hornblende and muscovite. Sample localities are illustrated on figure 2.

Table 1. Argon isotopic analyses.

S-40 #13. 14. &15 RD74 HORNBLENDE

J = 0.008336 + 0.50% SAMPLE WT = 1.0000 g

TEMP C	Initial & radiogenic 40 Ar	Potassium derived 39 Ar	Chlorine derived 38 Ar	Calcium derived 37 Ar	Initial 36 Ar	AGE* in Ma	**
1050	2.864E-11	3.210E-13	1.197E-14	2.614E-12	9.117E-15	624.99 +	1.70
1100	4.008E-11	1.109E-12	2.542E-14	8.483E-12	5.947E-15	456.79 +	.45
1130	7.411E-11	2.221E-12	4.249E-14	1.662E-11	4.148E-15	436.27 +	.15
1145	1.359E-10	4.160E-12	5.896E-14	3.041E-11	4.080E-15	431.08 +	.36
1160	1.866E-10	5.661E-12	8.757E-14	4.196E-11	5.323E-15	434.66 +	.29
1175	5.909E-11	1.809E-12	2.630E-14	1.324E-11	1.410E-15	431.78 +	.25
1190	6.086E-11	1.881E-12	2.853E-14	1.360E-11	1.351E-15	428.24 +	.31
1205	7.445E-11	2.302E-12	3.659E-14	1.655E-11	1.463E-15	428.46 +	.46
1220	8.471E-11	2.604E-12	3.941E-14	1.873E-11	1.121E-15	431.37 +	.27
1235	8.764E-11	2.661E-12	4.008E-14	1.923E-11	1.006E-15	436.25 +	.29
1250	6.388E-11	1.926E-12	2.867E-14	1.393E-11	***	439.02 +	.27
1350	9.827E-11	2.950E-12	3.877E-14	2.080E-11	***	441.15 +	.56
1450	1.655E-10	4.886E-12	6.405E-14	3.520E-11	2.355E-15	446.97 +	.34
1650	1.048E-10	3.096E-12	4.494E-14	2.222E-11	***	446.44 +	.55
TOTAL GAS	1.254E-09	3.759E-11	5.738E-13	2.736E-10	4.048E-14	439.08	

Points AJ deleted;
8 points regressed out of 10 includes 89.4 % of 39Ar
Mean X = .258E-01 Mean Y = .267E-03 Slope = -.382E-01 + .216E-02
36/40 = .125E-02 + .562E-04 39/40 = .328E-01 + .443E-03
Fit parameters: SUMS = 15.906 MSWD = 2.651
40Ar/36Ar = 798.33 + 35.81 F = 30.48 + .412 AGE = 408.73 + 5.27 Ma

S-45 #16, 17, &18 RD74 HORNBLENDE

J = 0.008343 + 0.50% SAMPLE WT = 1.0002 g

1075	6.487E-12	1.354E-13	2.660E-15	4.646E-13	3.217E-15	529.63 +	1.94
1130	4.400E-12	9.499E-14	3.924E-15	1.130E-12	1.951E-15	522.38 +	1.68
1150	4.568E-12	1.048E-13	5.160E-15	1.321E-12	1.615E-15	508.60 +	.70
1165	5.318E-12	1.386E-13	6.326E-15	1.767E-12	1.654E-15	460.48 +	1.89
1180	6.013E-12	1.559E-13	6.382E-15	2.095E-12	1.390E-15	473.01 +	1.29
1235	5.730E-11	1.759E-12	4.755E-14	2.193E-11	3.962E-15	425.75 +	.38
1235	2.931E-11	9.088E-13	2.350E-14	1.103E-11	2.257E-15	421.16 +	.46
1250	5.534E-12	1.616E-13	5.205E-15	1.961E-12	9.288E-16	433.40 +	.86
1350	1.402E-11	3.925E-13	1.315E-14	4.836E-12	1.897E-15	454.00 +	.90
1450	1.106E-11	3.068E-13	9.388E-15	3.727E-12	1.847E-15	453.79 +	.50
TOTAL GAS	1.440E-10	4.158E-12	1.232E-13	5.026E-11	2.072E-14	440.61	

S-42 MUSCOVITE #45RD85

J = 0.009319 * 0.50% SAMPLE WT = 0.0257 g

900	3.148E-11	1.180E-12	***	***	2.685E-15	391.29 *	.81
1000	3.366E-11	1.269E-12	***	***	***	395.89 *	.91
1100	1.605E-11	5.971E-13	***	***	***	400.65 *	1.30
1200	1.564E-11	5.812E-13	***	***	***	401.29 *	.44
TOTAL GAS	9.683E-11	3.627E-12	***	1.739E-15	4.294E-15	396.05	

NO PLATEAU

Note: all gas quantities are in moles. No blank correction.
* Ages calculated assuming initial 40Ar/36Ar = 295.5 * 0
** 1-sigma precision estimates are for intra-sample reproducibility.
** 1-sigma precision estimates for plateaux are for intra-irradiation package reproducibility.
*** below detection limit

depth, and that the basement-cover thrusts along either side of the synform are continuous. Basement sheets in this model are interpreted to be imbricated slivers, some 50 m thick, that are greater than ~60 km in width (Gustavson 1974). This style is considered thin skinned although the classical 'thin-skinned style' (Rogers 1949) does not typically involve basement. The second interpretation is referred to by Tull (1972, 1977) and Hodges et al. (1982) as the 'basement shortening' or 'thick-skinned' model. This model holds that during the subduction of Baltica, thick slabs of basement were imbricated and thrust eastwards in an in-sequence or piggy-back style. This led to the idea that the Western Gneiss Region basement-cover contact in Ofoten is part of the ancient A-type subduction zone boundary.

Bartley (1984), and later Björklund (1987), working in the same area directly south of the present study area on Hinnøy, recognized evidence for both models of basement-cover evolution. Bartley (1984) suggested that the Western Gneiss Region basement-cover contact on Hinnøy reflects a series of large Pennine-like basement-cored recumbent folds (>10 km amplitude) that formed as the overlying Caledonian allochthons were thrust eastward over the Fennoscandian Shield, which supports the thick-skinned model. The folds and the thrusts formed synchronously under kyanite-grade conditions. In contrast, Björklund (1987), working in the same rocks mapped by Bartley, reported six imbricated thrust-sheets, each consisting of thin basement granite slices with attached cover of the Lower and Middle Allochthons that were metamorphosed and emplaced under greenschist-facies conditions. This interpretation supports thin-skinned thrust imbrication of only the uppermost basement and its attached cover, which requires shallow crustal level conditions for the formation of the basement-cover contact. More recently, Andresen & Rykkelid (1991) have suggested a modification to this model in which the basement-cover contact is an out-of-sequence thrust that has brought greenschist-facies rocks into contact with the higher grade units.

Two major contradictions between the above models deserve consideration. First, metamorphic conditions for the formation of the basement-cover contact are strikingly different. Bartley reported evidence from Hinnøy for kyanite-grade conditions of emplacement, which is comparable to temperatures and depths estimated by Hodges et al. (1982). Björklund, on the other hand, reported petrologic evidence that some rocks along the basement-cover contact on Hinnøy never experienced temperatures and pressures greater than greenschist facies. Second, if the basement-cover contact is recumbently folded as in Bartley's model, then a mirror image of units should occur across the axial surface; thrust imbrication as suggested by Björklund would duplicate units without a mirror image repetition.

Results from our work on Sandsøya and Grytøya have implications for these models and indicate that the formation of the basement-cover contact involved certain aspects of all three models discussed above. First, amphibolite-facies minerals and fabrics are traceable through the contact between the cover units of the Altevik sequence and the overlying basement sliver which suggests that the basement-cover contact on these islands formed under amphibolite-facies conditions. Second, the basement and cover stratigraphy on Sandsøya and Grytøya is not repeated in a mirror image fashion but rather is duplicated by thrust imbrication as Björklund suggested. Third, there is obvious evidence for out-of-sequence thrusting. The Vetten schist sequence contains abundant kyanite, which is not common in the Lower/Middle Allochthons. In addition, on Sandsøya, parts of the Upper Allochthon, the Hallevika and Altevik sequences, structurally underlie imbricated basement and cover units of the Middle Allochthon. Similar structural relations are reported by Andresen & Rykkelid (1988) south of Storvatn on Hinnøy.

It is noted that this is the first published report of out-of-sequence thrusting along the Western Gneiss Region basement-cover thrust in western Ofoten. Andresen & Steltenpohl (1991) and Anderson et al. (1992) described an out-of-sequence thrust at mid-nappe stack levels along the east limb of the Ofoten synform. Large-scale out-of-sequence thrusting of rocks in this region, therefore, is a distinct possibility, though a better understanding of how this thrusting along the east limb of the Ofoten synform relates to that now recognized along the west limb is needed. Anderson et al. (1992) argued that the out-of-sequence thrust along the east limb of the Ofoten synform in areas north of Ofotfjord has repeated much of the entire preserved nappe stack as tectonic plate convergence progressed into the Devonian. Coker et al. (1995), on the other hand, suggested that the same out-of-sequence thrust may have formed in response to east-directed contractional movements resulting from gravitational collapse of the Western Gneiss Region hinterland.

Finally, a surprising result of our work is the recognition of left-slip, top-to-the-northeast movement along shallow, southeast-dipping shear zones that are associated with the basement-cover contact. Prior to this report, no kinematic studies had been reported along the basement-cover boundary in the study area. Workers in adjacent areas to the south traditionally had presumed, however, that this boundary was the locus of east-directed thrusting that emplaced the Caledonian allochthons (Gustavson 1972, Bartley 1981a, 1984, Björklund 1987, Rykkelid 1992). In addition to the left-slip shear-sense indicators reported herein, previously hard to explain, regionally developed, NW-SE-trending orogenic cross-folds and faults in this region (Steltenpohl & Bartley 1988, 1992) can be geographically, geometrically, kinematically, and temporally linked to left-slip movements along the basement-cover contact (Van Winkle 1994, Van Winkle et al. 1992). Although the significance of left-slip movements in the Norwegian Caledonides at this latitude is yet to be determined, the timing and kinematics of this event is compatible with observations from other parts of the Caledonian belt on both sides of the Atlantic Ocean (e.g., Harland & Gayer 1972, Van der Voo & Scotese 1981, Roberts 1983, Flinn 1985, Hutton 1987, Currie & Piasecki 1989, Grønlie & Roberts 1989, Robinson 1991, Hutton & McErlean 1991). Most workers have attributed orogen-parallel movements in the Caledonides to a transition from simple convergence to sinistral transpression occurring sometime during the Late Silurian and Devonian. This is consistent with our combined structural/microstructural observations and ^{40}Ar/^{39}Ar dates from western Ofoten which imply that left-slip motion occurred after the nappes were emplaced during Siluro-Devonian times.

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