Basement-cover relations and late- to post-Caledonian extension in the Leknes group, west-central Vestvågøy, Lofoten, north Norway

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Rocks underlying the Lofoten islands of north Norway have long been recognized as presenting significant problems for models proposed for Caledonian orogenic evolution. Lofoten occupies the most internal position of exposed rocks in north Norway, yet, remarkably, earlier workers report little or no Caledonian reworking of Precambrian basement rocks. Furthermore, a critical question prevails as to whether or not Lofoten experienced extreme magnitudes of extension like its Western Gneiss Region counterparts in southwest Norway. Geologic mapping and kinematic analysis of rocks exposed on west-central Vestvågøy, Lofoten, were done to address these problems. Results indicate progressive ductile sinistral shearing, ductile-brittle extension, and uplift of the region concurrent with or immediately following Caledonian (ca. 425 Ma) contraction. Slivers of tectonized Baltic basement granite overlain by allochthonous metasedimentary and metavolcanic/ metavolcaniclastic units of uncertain origin (the Leknes group) were thrust eastward over pre-Caledonian Baltic crystalline basement of the northern Western Gneiss Region. The emplacement of these allochthons onto the Lofoten basement (during D_1-D_2) was contemporaneous with partial subduction of the Baltic craton beneath Laurentia during the Caledonian orogeny. Following nappe emplacement, low-angle sinistral-oblique and normal plastic shear zones (D_3-D_4) formed parallel to the basement–allochthon contact and overprinted earlier Caledonian thrust fabrics. These late ductile shear zones record a top-west sense of shear and are locally cross-cut by top-west cataclastic normal faults (D_5), reflecting progressive unroofing of the shear zones to shallower crustal levels during late- and post-Caledonian extensional events. The normal faults and fabrics are interpreted to have episodically reactivated a Caledonian thrust during Devonian–Permian extensional collapse of the orogen. Northeast-trending, high-angle, brittle normal faults (D_5) that occur throughout Lofoten-Vesterålen are interpreted to have formed during Permian or Jurassic–Cretaceous faulting events. Results of this study suggest that rocks exposed in Lofoten experienced extension that was roughly contemporaneous with phenomenal extension in southwest Norway, but of a lesser magnitude. Furthermore, extension in Lofoten is interpreted to have been accommodated by many discrete shear zones rather than along one or two master detachments, as was the case in southern Norway.

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Introduction

The contractional history of the northern Caledonian orogen has been the topic of numerous published papers, but late- to post-Caledonian extensional activity in northern Norway has been only generally explored. Caledonian thrusting is known to be east-southeast-directed throughout Scandinavia (Gee 1975; Roberts & Gee 1985) and west-directed in Greenland (Haller 1971) and northern Scotland (Powell & Glendinning 1990), consistent with the interpretation that the ancient Iapetus Ocean was consumed in between. Since the 1980s, high-precision isotopic dating methods have documented rapid and, in some cases, extreme hinterland uplift and cooling that supports large-scale extension in an evolving orogen (Selverstone 1988; Andersen et al. 1991; Burchfiel et al. 1992; Steltenpohl et al. 1993). These findings have resulted in a re-evaluation of global tectonic regimes, and point toward lithospheric extension as an important mechanism that explains the rapid rise and denudation of the metamorphic cores of orogenic belts (Wernicke 1985, and references above). Orogenic collapse of topographically high mountains due to gravitational instability may also explain why some oceans preferentially begin to open along the axes of ancient collisional belts (Dewey 1988). The Lofoten region of north Norway is an ideal place to investigate this phenomenon, since it must have occupied a position at or near the core of the Caledonian orogenic welt.

Given the assumed internal position of the Lofoten region during Caledonian orogenesis, there has been much controversy as to why much of the basement in Lofoten appears to have experienced little or no Caledonian deformation (Tull 1977; Griffin et al. 1978; Bartley 1981). The lack of basement deformation in Lofoten contrasts sharply with the penetrative deformation of the Western Gneiss Region (WGR) exposed in west Norway, ca. 800 km to the south. Shear zones in Lofoten are concentrated along the basement–allochthon contact and near supracrustal enclaves within the basement. This observation is consistent with the interpretation that deformation decreased structurally downwards during Caledonian orogenesis. This phenomenon has been observed elsewhere in Scandinavia, but it is more accentuated in Lofoten due, perhaps, to the 'dry' nature of the predominantly mangeritic basement (see below, Discussion; see also Bartley 1982).

Metasedimentary/metavolcanic rocks exposed in the hinterland regions of the Caledonides have generally been interpreted to be associated with one of two tectonostratigraphic settings: (1) pre-Caledonian autochthonous/parautochthonous inliers or slivers within the Baltic basement; or (2) allochthonous rocks of the composite Caledonian allochthon. Assigning rocks to one setting or the other has often proved to be problematic, especially where the contact between these rocks and the granitic basement is poorly exposed. The island of Vestvågøy contains extensive exposures of Baltic basement and metasedimentary/metavolcanic rocks (Leknes group of Tull 1973), and, most importantly, the contact between these two rock types is well-exposed near the town of Leknes. The contact, examined in detail by Tull (1973, 1977) and again in this study, is interpreted to be a fault that juxtaposes the Leknes group against the basement, based on the facts that the contact is mylonitized and that the degree of mylonitization increases as the contact is approached. The increased mylonitization, coupled with a lack of evidence for either intrusive or sedimentary origin, suggests that the Leknes group is allochthonous to some degree with respect to the underlying Baltic basement. The allochthonous nature of the Leknes group raises two critical questions:

1. When was the Leknes group emplaced against the basement?
2. If such a juxtaposition took place during the Caledonian orogeny, is the Leknes group correlative to any of the allochthonous rocks exposed in the Caledonian nappe stack on the mainland?

Herein we present detailed structural and fabric analyses of rocks along the basement–allochthon contact, as well as from overlying terranes of the Leknes group to evaluate: (1) the relationship of the Leknes group to its basement; (2) the degree of Caledonian deformation in the basement; (3) the effects of post-Caledonian extension in the region; and (4) the role of the Leknes group in the tectonostratigraphic evolution of the north Norwegian Caledonides.

Geologic setting and previous investigations

Islands of the southern Lofoten archipelago are predominantly composed of ca. 1700–1800 Ma mangeritic and charnokitic intrusions referred to as the 'mangerite suite' (Griffin et al. 1978). These intrusions, composing the bulk of the WGR basement in Lofoten, were emplaced under granulite-facies conditions, and later locally retrograded to amphibolite facies in shear zones accompanying allochthonous Caledonian rocks (Tull 1973, 1977; Griffin et al. 1978). On the island of Hinnøy, ca. 100 km to the northeast of Vestvågøy, exposures of metasedimentary and metavolcanic rocks occur: (1) as pendants or blocks that have been intruded by the mangerites (Hesjevann assemblage and Kvæfjord Group of Bartley 1980); or (2) in stratigraphic contact with the mangerites, either pre-dating (Austerfjord Group of Hakkinen 1977) or post-dating (Storvann Group of Bartley 1980) the ca. 1380 Ma intrusion of the Lødingen granite. These sequences are considered to be autochthonous or parautochthonous with respect to Baltica, and were thus tectonically buried by the Caledonian allochthons (Bartley 1982).

Many geologic investigations have focused on the composite Caledonian allochthon and underlying Baltic basement in the Ofoten–Efjorden–Rombak region of north Norway (see, for example, Hodges et al. 1982; Steltenpohl 1983, 1987; Andresen & Tull 1986; Steltenpohl & Bartley 1988; Northrup 1996). These studies have elucidated the tectonostratigraphy and structural evolution of the nappe stack on the mainland, but questions remain as to how lithologies exposed in the Lofoten islands (68°N) (Fig. 1) might relate to the Caledonian nappes. Several of these islands expose macroscopic (5–15 km-thick) lenses of metasedimentary and metavolcanic/metavolcaniclastic rocks that are in fault contact with the deep-crustal basement of the WGR (Tull 1977; Griffin et al. 1978; Bartley 1980). Fault-bounded rock associations of the Leknes group (Tull 1973, 1977) are exposed on the islands of Vestvågøy, Værøy, and Røst (Sigmond et al. 1984; Holloman et al. 1995). The type locality on Vestvågøy (Tull 1977) comprises aluminous schist, calc-silicate gneiss, quartzite, marble, amphibolite, and voluminous

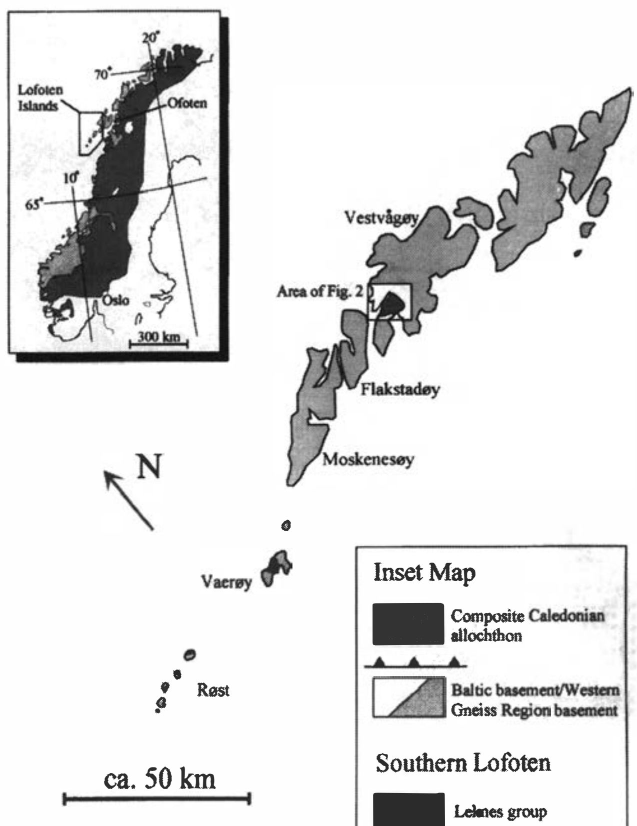


Fig. 1. Location of the Lofoten archipelago and study area (see Fig. 2 for detailed map). Lithologies exposed in Lofoten are primarily Archean basement gneiss of the Western Gneiss Region (gray) and allochthonous metasedimentary rocks of the Leknes group (black). The Ofoten region of north Norway is indicated.

quartzofeldspathic mica schist (Fig. 2). The tectonostratigraphic affinity of the Leknes group is unclear, but is a key to understanding the Caledonian and later tectonic evolution of the continental margin at this latitude. The isolated nature of the Lofoten islands has led to uncertainty about whether Lofoten basement rocks are continuous with the Baltic basement (Tull 1973, 1977; Griffin et al. 1978; Bartley 1981, 1982). Recent papers, however, use high-precision geophysical methods to document clearly continuity between the Lofoten block and the Baltic basement (Løseth & Tveten 1996; Olesen et al. 1997).

At the time of this writing, there are few published geochronologic data to constrain the Caledonian history of Lofoten. Griffin et al. (1978) reported a poorly defined five-point Rb-Sr whole-rock 'isochron' age from the Leknes group metasediments of 1140 ± 135 Ma. Later, Sutter (cited as pers. comm. in Tull 1973 and Tull et al. 1985) used K/Ar and $^{40}Ar/^{39}Ar$ geochronology to further constrain the cooling history of the Lofoten region to the interval from 530 Ma (uncertain age of hornblende) to 350 Ma (muscovite and biotite), implying Caledonian reheating of this region. Based on the available data, Tull (1973) interpreted two separate amphibolite–facies metamorphic events having affected rocks in Lofoten; the first is the M_2 event described in his study, which 'has a possible age range of 160–520 million years' (p. 87), and the second is the Caledonian metamorphism observed on eastern Hinnøy, where outcrops are continuous with rocks exposed on the Norwegian mainland, and where they are clearly documented as having been metamorphosed during the Silurian–Devonian Scandian event (Bartley 1980). To address the question of timing of metamorphism in the Leknes group, Hames & Andresen (1996a, 1996b) analysed porphyroblasts from Leknes group rocks using the $^{40}Ar/^{39}Ar$ laser method. Their results support tectonothermal development during the interval from ca. 425 Ma to ca. 265 Ma. Hames & Andresen (1996a) interpret that radiogenic ^{40}Ar retention in a muscovite porphyroblast from Vestvågøy began near the core of the crystal during, or soon after, crystal growth in the Silurian, Scandian phase of the Caledonian orogeny (at ca. 425 Ma). This age is consistent with 420–380 Ma ages on hornblende from amphibolites in the Leknes group (Hames & Andresen 1996b). Based on observations made during the present study, and due to the uncertainties in the available whole rock and hornblende ages from Vestvågøy when Tull published his reports, the present authors interpret that only one Caledonian amphibolite–facies metamorphic event affected rocks of the allochthonous Leknes group cover in Lofoten.

Tectonostratigraphy and structural geology

The tectonostratigraphy of the Leknes group, originally described by Tull (1973, 1977), has been re-examined along the basement–allochthon contact in order to evaluate better the nature of these rocks and their relationship to the underlying basement (Fig. 3). A much more thorough description of lithologies is given in Klein (1997), and only those aspects of the tectonostratigraphy integral to interpreting the nature of the basement–allochthon contact are given here.

Rocks of the study area have experienced at least five episodes of deformation. Detailed structural and petrographic analyses indicate that these events can be broadly grouped into two amphibolite–facies events (D_1 and D_2), followed by three post-metamorphic events (D_3 through D_5) that occurred under relatively lower-grade conditions. The first two deformations are interpreted to be associated with Caledonian nappe emplacement. Late syn- to post-Caledonian deformations produced ductile and brittle shear zones in the basement complex and allochthonous cover units. In the following description, from the oldest to the youngest event, structures and fabrics resulting from a particular deformational event are numbered ($D_1 = L_1$, S_1, and F_1, 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. Petrographic evidence for D_1 deformation is rare and limited to inclusion trails in M_2 garnet poikiloblasts. S_i in the poikiloblasts is commonly rolled or snowballed, and is discordant with the surrounding S_e foliation, S_2, which is defined by M_2 mineral assemblages (see Fig. 3 – *Lower laminated amphibolite* and *Silver garnet mica schist*). S_i in the garnets most likely preserves the only record of S_1 in the Leknes group metasediments, but the origin of S_1 is unresolved. It may reflect a compaction cleavage in the sedimentary protoliths. Alternatively, S_1 might reflect a fabric generated during an earlier metamorphism (Tull 1977).

D_2 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 lower- to middle-amphibolite–facies (staurolite- and kyanite-zone) mineral assemblages.

F_2 folds are present in practically all rock types. They are tight to isoclinal folds in amphibolite and quartzofeldspathic mica schist with similar fold styles (Ramsay 1967). F_2 folds S_1, resulting in a general parallelism of S_1 and S_2. Scales of the folds vary from a few centimeters to nearly a meter, with amplitude to wavelength ratios of approximately 7:2. F_2 folds in the field area appear to correspond to the F_2 folds of Tull (1973), and are most commonly observed along the basement–allochthon contact. Isoclinal F_2 folds are recumbent, with subhorizontal axial planes and axes that plunge shallowly to the northeast. Due to the bidirectional subhorizontal nature of F_2 axial planes, the vergence of F_2 folds cannot be used as a definitive

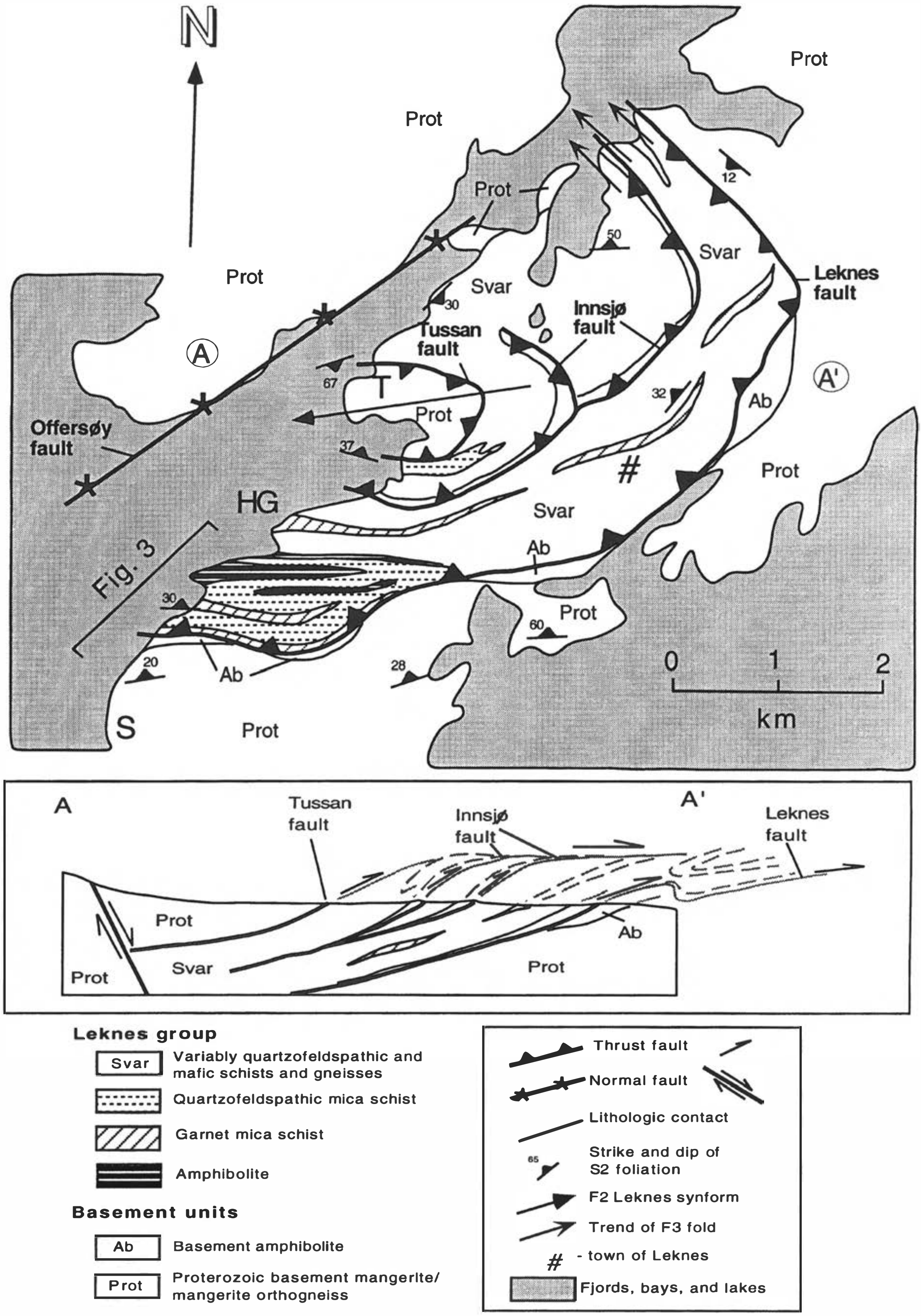
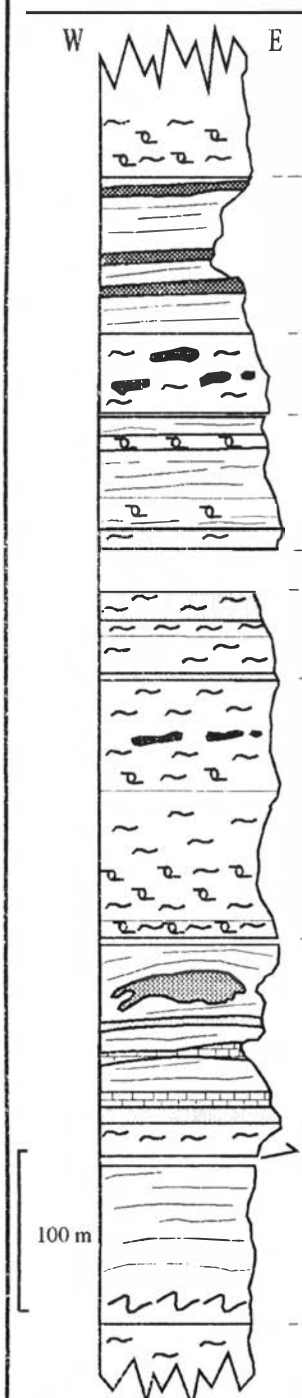


Fig. 2. Lithotectonic map of the study area and diagrammatic cross-section A-A' (same horizontal scale as map). Rock types illustrated are general lithologies only. See Fig. 3 for detailed description of units along basement–allochthon contact. Place names used for reference in the text: HG = Hauge; O = Offersøya; S = Sund; T = Tussan.



Rock Type	Struct. & Microstruct. Observations
Quartzofeldspathic mica schist	Asymmetrical feldspar porphyroclasts have a consistent top-west sense-of-shear. Rootless intrafolial folds of S2 verge toward the west, suggesting west directed transport of structurally higher rocks. M2 mineral assemblages are retrograded from amphibolite facies to greenschist facies in narrow shear zones, and M2 bladed or platy minerals are commonly bent or broken
Interlayered amphibolite and tonalite (crossed pattern).	
Mica schist with amphibolite pods.	Microscopically, narrow (<0.5 mm) shear zones contain ravelled biotite and chlorite. Rare kyanite is twinned and broken
Quartzofeldspathic mica schist, garnet mica schist, and amphibolite.	A late brittle fault (Hauge fault of Klein 1997) is subparallel to S2 and defines an extensional crenulation cleavage (S4) along which structurally higher rocks were transported. Kinematic analysis of S-C fabrics adjacent to this fault indicates that the sense-of-shear was top-west during D4 brittle-ductile faulting (see text)
Gap, due to non-exposure.	
Quartzofeldspathic mica schist and quartzite.	Muscovite commonly occurs as large fish, the asymmetry of which indicate a top-west sense-of-shear. Small shear bands offset S2 in a top-west sense-of-shear
Quartzofeldspathic mica schist with amphibolite pods (black) - commonly contains large (1-2 cm) white and pink feldspar porphyroclasts	Mesoscopically, late shear zones crosscut the S2 schistosity; sense-of-shear is consistently top-west (see Fig. 8); chlorite replaces biotite. Asymmetrical feldspar porphyroclasts (in strat column at left) have a consistent top-west sense-of-shear. Microscopically, kyanite is commonly bent or twinned and biotite is ravelled (see below). Zones of high strain marked by very fine-grained (<0.25 mm in diameter) qtz and feldspar contain large (0.5 - 2 mm) mica fish indicating a top-west sense-of-shear
Interlayered amphibolite (lined), calc-silicate gneiss (stipple), and marble (brick) with gabbro pod (cross hatch)	Mesoscopic F3 folds are common in this unit along the southern part of the basement-allochthon contact, where they are rarely observed to refold F2. M2 metamorphic peak minerals are commonly retrograded (e.g. biotite after garnet), and mica crystals have a ravelled appearance (sheared, kinked, and peeled with minor recrystallization along the margins). Small (<2 m in diameter) mafic bodies are relatively undeformed
Silver garnet mica schist	Si in garnet discordant with Se; top-east shear sense
Lower laminated amphibolite - alternating bands of qtz + fspar and garnet + amphibole	Composite fabric at base of unit contains steeply-dipping S1 sheared into parallelism with subhorizontal S2 along narrow (<5 cm wide) shear bands; offset along S2 bands has a consistent top-east sense-of-shear. Poikiloblastic garnets have curved inclusion trails of qtz and plagioclase, Si discordant with Se; shear sense is also top-east
Proterozoic Baltic basement (mangerite)	West-vergent backfolds along basement-allochthon contact are consistent with top-west sense-of-shear recorded in structurally higher rocks (see above)

Fig. 3. Detailed tectonostratigraphic column illustrating lithologies of the Leknes group exposed along the beach from Sund northward across strike to Hauge (see Fig. 2 for location). Structural and microstructural observations are summarized from Klein (1997).

kinematic indicator during D_2, suggesting that a large component of coaxial flattening strain may have been accommodated by more competent rock layers near the basement–allochthon contact.

Two main fabric elements were produced during D_2, the dominant S_2 schistosity and an L_2 mineral lineation. S_2 is defined by lower to middle amphibolite–facies, staurolite- and kyanite-zone assemblages. The S_2 foliation parallels the basement–allochthon contact (Fig. 4). Stereographic projections of S_2 indicate gentle to moderate dips to the west and northwest throughout much of the study area, with gentle dips to the east and southeast in the northwestern part (Fig. 5), defining a broad synform about which S_2 has been folded. S_2 is traceable structurally downward for approximately 50–200 m beneath the basal contact into the basement mangerite, but gradually disappears, occurring only in anastomosing shear zones that may or may not parallel the basement–allochthon contact to depths approaching several kilometers. The gradual disappearance of S_2 with depth is a relation recognized regionally along the northern WGR basement-cover contact (Tull 1973; Bartley 1981; Hodges et al. 1982). Fabric-forming hornblende yields $^{40}Ar/^{39}Ar$ ages of 425–385 Ma on Vestvågøy (Hames & Andresen 1996b), which is consistent with crystal growth during Caledonian amphibolite–facies metamorphism.

A rarely observed L_2 mineral lineation, defined by the parallel alignment of hornblende, kyanite, biotite, and muscovite, parallels F_2 isoclinal fold axes and plunges shallowly to the northeast. The rarity of observed L_2 fabrics may be the result of intense overprinting by a later L_4 stretching lineation. It was also observed, however, that L_2 was restricted mainly to the D_2 shear zones and was simply never developed outside of them.

The fault at the base of the Leknes group, informally named the Leknes fault (Fig. 2), is interpreted to be a D_2 structure (Tull 1973, 1977; Klein 1997), but the kinematics have previously been unresolved. The timing of movement along the Leknes fault has been poorly constrained to the interval from 1600–520 Ma (Tull 1973) and, more specifically, from 1150–900 Ma (with large error, ±135 Ma) (Griffin et al. 1978). Clear overprinting relations between S_1 and S_2 in the amphibolite unit along the basement–allochthon contact (see above, *D_1 deformation*, Fig. 3) document shearing of the subvertical S_1 compositional layering into subhorizontality in narrow (<5 cm) shear zones that parallel S_2 in the overlying Leknes group. Offset of the subvertical layers above the shear zones toward the east-southeast relative to those below the shear zones is observed in many places as the layers are traced across the narrow shear zones (Klein 1997). This cross-cutting relationship between S_1 and S_2 suggests east-southeast-directed transport of overlying Leknes group rocks, which is consistent with transport direction for the composite Caledonian allochthon. This structural evidence, combined with available timing information (Hames & Andresen 1996a, 1996b), favours the idea that the Leknes group was emplaced upon the basement along a Caledonian thrust. Alternatively, the contact might be a late-Caledonian, top-east normal-slip shear zone (e.g. Coker et al. 1995).

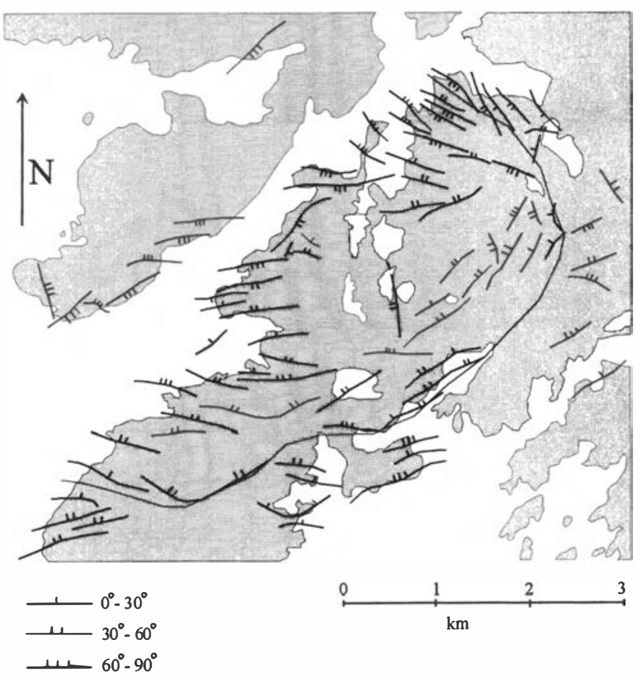


Fig. 4. Structural form-line map of the study area. Long lines are parallel to strike of dominant foliation S_1/S_2; tick marks point in dip direction and denote relative amount of dip. Note continuity of foliation across the basement–allochthon contact (thin line), especially in the northern and southern parts of the study area.

Two other fault contacts, interpreted to be D_1 or D_2 structures, were mapped within the Leknes group (Fig. 2). These faults, which generally parallel S_2, are interpreted to be thrusts based on the juxtaposition of slivers of granitic basement rock on top of the Leknes group units. The structurally lowest of these two thrusts, informally named the Innsjø fault for its proximity to a small lake, represents a distinct lithologic break within the Leknes group and is marked by a basement sliver that strongly resembles deformed Tysfjord granite gneiss of the northern WGR in Ofoten and Tysfjord (Gustavson 1966; Andresen & Tull 1986; Van Winkle et al. 1996). The lower contact of the granite sliver is marked by an intensified mylonitic foliation, seen as a reduction of large (4 cm in diameter) feldspar porphyroclasts becoming more isolated and smaller structurally downward. The mylonitic foliation is defined by amphibolite–facies mineral assemblages, implying that the granite sliver was thrust upon the Leknes units during the metamorphic peak.

The structurally highest of the thrusts, informally named the Tussan fault, has been inferred between the silicified, mangeritic basement orthogneiss exposed on the Tussan peninsula, and Leknes group units structurally below this mangerite unit (Fig. 2). Tull et al. (1985) recognize this boundary as a thrust as well, due to the fact that it juxtaposes basement rock structurally above metasedimentary rock units exposed in the core of the Leknes synform (Fig. 2).

D_3 and D_4 deformation

D_3-D_4 structures and related fabrics deform and overprint all earlier structures. Structures and fabrics associated with these two events are interpreted to record the transition from amphibolite- to greenschist–facies conditions subsequent to, but perhaps partly overlapping with, D_2 nappe emplacement. Separating D_3 and D_4 is difficult because of similarities in fold style and metamorphic grade, and because fold interference patterns between F_3 and F_4 were never observed. These events are therefore treated together, with differences pointed out. D_3-D_4 events

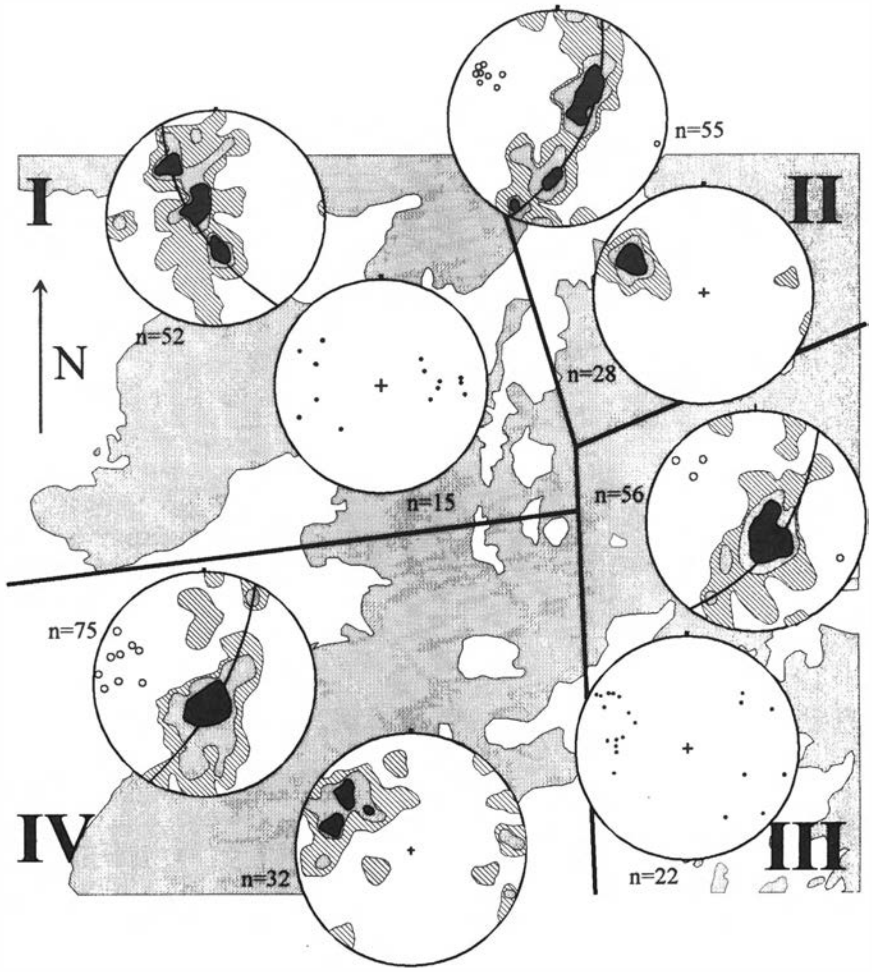


Fig. 5. Lower-hemisphere equal-area projections of mesoscopic structural data for four subareas. *Upper stereonet* in each subarea is a plot of poles to S_1/S_2 (contoured) along with F_3 fold axes (open circles in subareas II, III, and IV). Note great circle through poles to S_1/S_2 indicating later folding by F_3. *Lower stereonets* plot L_4 stretching lineations (black dots, contoured where $n > 25$). Subarea I contours are 1, 2, and 4% per 1% area. Subarea II contours are 1, 2, and 6% (foliation) and 2, 10, and 20% (lineation). Subarea III contours are 1, 2, and 6%. Subarea IV contours are 1, 2, and 6% (foliation) and 2, 6, and 8% (lineation).

occurred on Vestvågøy as early as 390 Ma and continued throughout the interval 390–360 Ma based on $^{40}Ar/^{39}Ar$ mineral ages reported by Hames & Andresen (1996a).

D_3 and D_4 folding

Two distinct fold sets, F_3 and F_4, fold the S_2 schistosity and mylonitic foliation. F_3 folds have gentle to moderate (<50°), west-northwest plunging axes (Fig. 5) and axial planes that dip steeply to the southwest and northeast. They are open to tight concentric folds in amphibolite and chevron folds in mica schist. Scales of the folds vary from a few centimeters to a kilometer or more. Amplitude to wavelength ratios rarely exceed 2:1. F_3 sheath folds with northwest-trending axes were observed to fold L_2 along the beach ca. 4 km north of Sund, and are attributed to late shearing.

F_4 folds were rarely observed and have moderately plunging, north-northeast trending axes with east-dipping axial planes (Fig. 6, Fig. 3 – *Proterozoic Baltic basement*). They are concentric in style and are commonly asymmetric. Scales of the folds vary from a few cm to 0.5 m, with amplitude to wavelength ratios rarely exceeding 2:1. F_4 fold axes parallel the orogenic trend, but verge to the west in the opposite sense from that of nappe transport, and thus are considered backfolds (Steltenpohl & Bartley 1988). F_4 fold formation appears to have been by flexural slip within the S_2 layers, and the folds are thus considered to have formed under retrogressive metamorphic conditions (Tull 1973). The fact that F_4 folds are found in proximity to retrogressive shear zones (see below, D_4

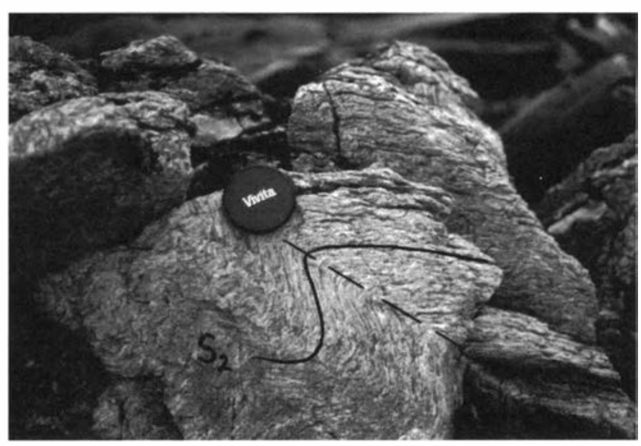


Fig. 6. Outcrop photo of a mesoscopic F_4 backfold in basement mangerite orthogneiss, looking north and down-plunge, ca. 1.25 km north of Sund. Note west vergence of axial surface and lack of axial planar fabric.

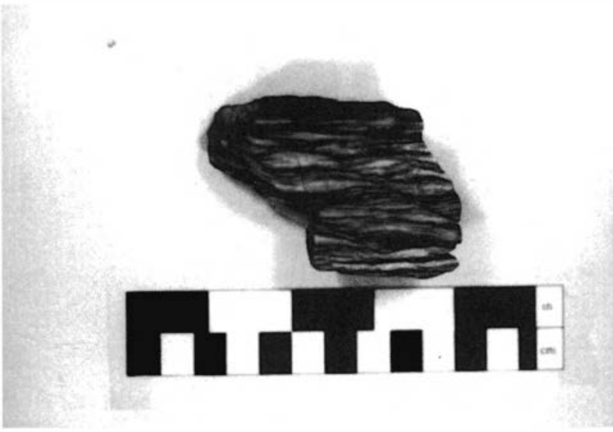


Fig. 7. Oriented hand sample of sheared basement mangerite from quarry ca. 1.5 km southwest of Leknes. Sample was cut perpendicular to the mylonitic foliation and parallel to the elongation lineation. Note subhorizontal S_2 fabric offset along S_4 extensional shear bands dipping shallowly to the right (west). Scale is in inches over centimeters.

ductile shearing) suggests that F_4 folds formed under greenschist–facies metamorphic conditions.

D_4 ductile shearing

Top-west, ductile shear zones that affect the basement and cover units of the study area are interpreted as D_4 structures (see Fig. 3). These northeast-trending shear zones are typically less than 2 m thick in the basement lithologies, but a related ductile shear zone in the cover approaches 1 km in thickness. An extensional crenulation cleavage (Platt & Vissers 1980) (S_4) forms local S-C composite planar fabrics (Lister & Snoke 1984) in the basement (Fig. 7) and S-NSC (Dennis & Secor 1987)

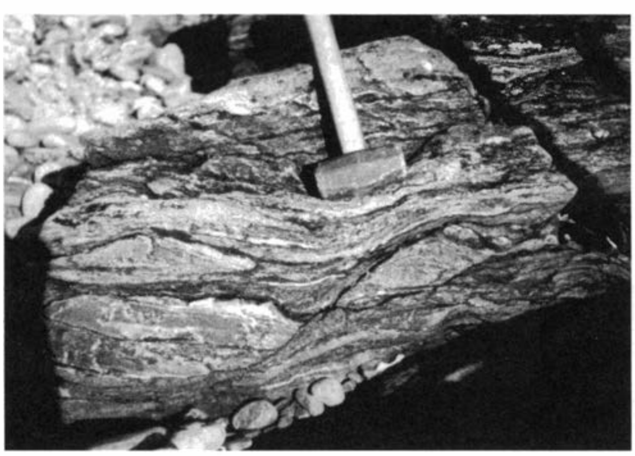


Fig. 8. Interlayered quartzite and quartz-rich mica schist exposed on the beach, ca. 3.25 km west of Leknes. View is looking north and down the dip of the dominant schistosity. The schistosity in the rock is offset in a top-down-to-the-west sense-of-shear.

composite fabrics in the cover units (Fig. 8). This cleavage is most likely related to D_4, based on its concentration within late ductile shear zones that overprint F_3 folds. Also related to D_4 is an S_4 mylonitic foliation in the basement lithologies that parallels the S_4 extensional crenulation cleavage in the cover, and is most strongly developed within late ductile shear zones.

Microscopically, the mylonitic foliation is defined by a reduction in grain size, the development of quartz ribbons, and incomplete grain recrystallization (subgrains). The shear zones overprint D_1-D_3 fabrics and structures, and associated S_4 fabrics are generally subparallel to S_1/S_2. In the relatively isotropic basement units, the shear zones generally are randomly dispersed but concentrated near the basement–allochthon contact. Isotropic undeformed basement mangerite can be traced progressively into an ultramylonite within these shear zones, the transformation from mangerite to ultramylonite usually taking place within a few centimeters. A mineral elongation lineation (L_4) in the S_4 mylonitic foliation is defined by stretched quartz and feldspar grains, and has a consistent shallow to moderate west-northwest plunge. The recrystallized tails of asymmetrical feldspar porphyroclasts are commonly observed to be parallel to L_4. The sense-of-shear recorded by these rotated porphyroclasts is consistently top-west (see Fig. 3). Based on the above shear-sense observations, L_4 is interpreted to indicate the line of transport.

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, grain-shape preferred orientations in quartz, S-C composite planar fabrics, and extensional shear bands (ESBs) all document shallow down west-northwest transport, with a sinistral component, along shallow north-northwest-dipping shear surfaces. Stereographic projections of extensional shear band surfaces connected along their common great circle indicate that displacement along the shear band surfaces was top toward the west-northwest. Slip-lines, determined by taking the acute bisectrix of the intersection of S_2 planes with extensional shear bands and S-C, which lie in the C-plane, and projecting them 90° along their common great circle in the direction of transport, cluster primarily in the northwest quadrant for ESBs, corroborating top-northwest directed movement within the Leknes group metasediments.

Phyllonite zones within the structurally lower parts of the Leknes group parallel the shear zones in the basement, and have the same top-northwest sense of displacement. These phyllonite zones in the southwestern part of the study area contain large 'buttons' of mica (<3 cm in length). 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 defines the kyanite-zone S_2 schistosity. Based on their proximal occurrence and similar orientations, kinematics, and deformational conditions, the phyllonite zones are inter-

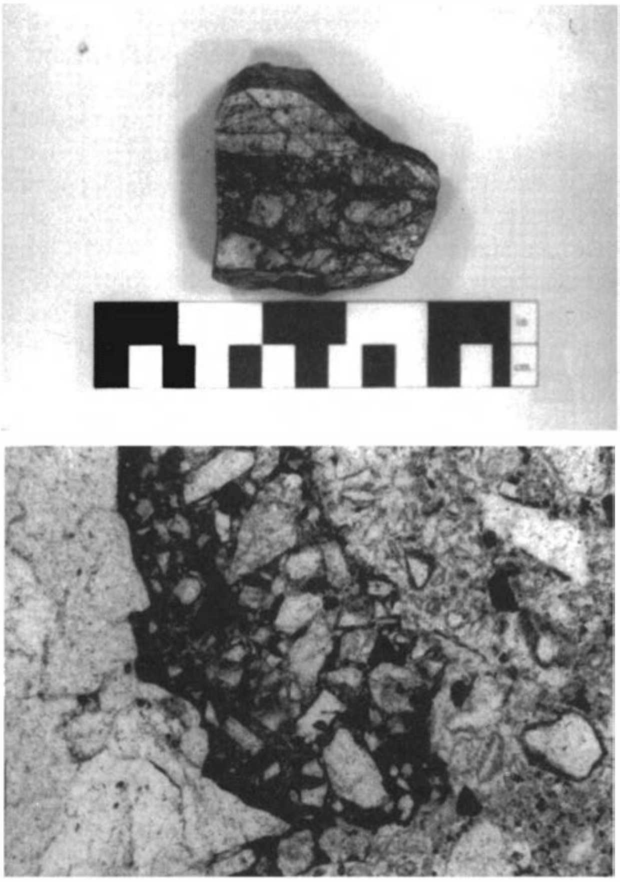


Fig. 9. Top. Polished slab of brecciated orthogneiss from late fault zone. Scale is in inches over centimeters. *Bottom.* Photomicrograph of brecciated orthogneiss with fragmented quartz grains. Note hematite (?) haloes and quartz overgrowths surrounding quartz grains. Field of view in bottom photo is ca. 2 mm, plane light. Both samples taken from Offersøya peninsula, ca. 5 km west-northwest of Leknes.

preted to have formed simultaneously with ductile shearing in the basement.

D_5 brittle faulting

A subvertical, northeast-trending breccia zone truncates the basement–allochthon contact on Vestvågøy, and is interpreted to be a late-phase, high-angle, down-east fault. The fault cuts massive and mylonitized mangerite orthogneiss. Breccias containing clasts of mylonite are exposed in a road-cut on the eastern shore of the Offersøya peninsula, and cataclastic rocks are also exposed in the northwestern part of the study area and on the northeastern tip of neighbouring Flakstadøy. The brecciated rock is light pink- to buff-coloured with purple hematite veins between granite clasts (Fig. 9, top). Small (<1 cm) euhedral magnetite grains are common. In thin section, quartz grains commonly have opaque (hematite?) haloes and quartz overgrowths (Fig. 9, bottom). Other late-phase brittle faults (D_5?) recognized in the area deform units of the overlying Leknes group.

Discussion

Nature of the Leknes group and basement–cover relations

A detailed re-examination of the basement–allochthon contact on Vestvågøy requires a re-assignment of the basal amphibolite unit (Leknes group lower amphibolite of Tull 1973, 1977). The present authors interpret the amphibolite at the base of the Leknes group to be part of the basement for the following four reasons:

1. Although the outcrop pattern of the amphibolite appears concordant on an outcrop scale, it is clearly discordant on a map scale, pinching and swelling along strike. If the contact between the amphibolite and the basement is indeed a thrust (Tull et al. 1985), the thrust must cut both up and down section along strike, which is unlikely.
2. The contact between the amphibolite and the basement is well exposed along the Hauge beach section near Sund (Fig. 2), and, although the contact is tectonized, it does not appear to be a major thrust boundary. Snowballed garnets throughout the amphibolite unit record an east-southeast transport direction for structurally higher rocks, favouring the interpretation that the amphibolite was overthrust by the Leknes fault. This interpretation is consistent with east-southeast-directed Caledonian thrusting throughout the region (Gee 1975; Roberts & Gee 1985; Steltenpohl 1987).
3. Orientations of quartzofeldspathic layers in the amphibolite are subvertical and similar to orientations of identical amphibolite layers in the basement on the Offersøya peninsula (Fig. 2). This layering is interpreted as being originally oriented at a high angle to the dominant subhorizontal foliation in the overlying Leknes group caused by thrusting. The origin of the earlier banding is unknown, but due to its steep dip it is unlikely that the banding is related to compositional layering found elsewhere in the Leknes group.
4. Finally, Van Winkle (1994) and Van Winkle et al. (1996) document the presence of an amphibolite unit within the Tysfjord Granite of the WGR in western Ofoten that appears to have partly controlled the position of the directly overlying basal Caledonian thrust. The amphibolite in western Ofoten is strikingly similar in its lithologic makeup and appearance, and is clearly intruded by the encapsulating Tysfjord Granite, firmly establishing it as part of the basement complex. The amphibolite described by Van Winkle et al. (1996) also occurs in exactly the same tectonostratigraphic position, and similarly pinches and swells along strike.

The tectonostratigraphic relations described above for the basement–allochthon contact provide a compelling argument that the Leknes group is in fault contact with the underlying Baltic basement. This interpretation, first advanced by Tull (1973, 1977), is supported by two additional observations: (1) The Leknes group is nowhere observed to be intruded by basement rocks, which is consistent with observations by Tull (1977) and Tull et al. (1985), and supports the idea that the Leknes group was not present during intrusion of the mangerite suite (ca. 1700–1800 Ma). (2) Lithologies exposed along the basement–allochthon contact do not represent the common fining-upward sequence typically observed in cover rocks deposited directly on the basement in north-central Norway (i.e. a basal conglomerate or orthoquartzite overlain by marble and schist, e.g. on Hinnøy [Bartley 1980, 1982] and in the foreland [see Tull et al. 1985]). Furthermore, the contact is tectonized, and snowballed garnets in rocks on either side of the contact record synkinematic rotation consistent with faulting during garnet growth.

The question of whether it is possible to correlate the Leknes group with units elsewhere in Norway is a critical one to tectonic models of the northern Caledonides. The difficulty lies in the fact that lithologic contacts are not directly traceable from the island of Vestvågøy to exposures of metasediments on nearby islands (Fig. 1). In addition, the apparent disappearance to the west of the mid-level nappes on the Norwegian mainland east of Ofoten (Andresen & Steltenpohl 1994) makes cross-strike regional lithologic comparisons difficult, and Lofoten is physically separated from the Norwegian mainland by the ca. 100 km wide bay Vestfjorden.

The islands of Værøy and Røst southwest of Vestvågøy (Fig. 1) contain lithologies that are similar in appearance to parts of the Leknes group (Sigmond et al. 1984). Værøy has a thick sequence of amphibolite, micaceous quartzite, and kyanite–garnet mica schist in the hanging wall block of a Caledonian thrust that resembles rocks in the southern limb of the Leknes synform (Mooney 1997). Islands of the Røst archipelago likewise contain sequences of amphibolite, biotite schist, kyanite–garnet two-mica schist, and minor marble that resemble lithologies within the Leknes group (Holloman 1996). Sequences on Røst are also exposed structurally above imbricated Caledonian thrusts (Holloman 1996; Waltman 1997).

Previous suggestions as to the timing of movement along the Leknes fault (Tull 1973, 1977; Tull et al. 1985) have been highly suspect due to the large errors inherent in the Rb-Sr method. The present authors find the lack of reliable existing age data that might constrain the timing of faulting to be inconclusive (see Griffin et al. 1978; Tull et al. 1985). In this regard, Caledonian cooling ages have recently been found to be the rule in Lofoten (Hames & Andresen 1996a), documenting that the Lofoten terrane was substantially reheated during the Silurian. Recent geochronologic studies indicate that D_2, fabric-forming, synkinematic hornblende records amphibolite–facies metamorphism at ca. 420–390 Ma (Hames & Andresen 1996b), consistent with the interpretation that the basal Leknes group thrust is Caledonian in age. Furthermore, cross-cutting relationships between S_1 and S_2 clearly demonstrate east-southeast-directed transport of Leknes group units onto the basement, consistent with models proposed for Caledonian thrusting throughout north Norway (e.g. Gee 1975; Roberts & Gee 1985; Steltenpohl 1987). Leknes group units on Vestvågøy, and similar sequences exposed on Værøy and Røst (Sigmond et al. 1984; Holloman et al. 1995) may, therefore, be correlative with Caledonian allochthons exposed in the nappe stack farther east (Klein 1997). The Leknes group shares lithologic similarities with the Narvik Group (Narvik nappe complex of Andresen & Steltenpohl 1994) of western Ofoten, and with the Seve nappe of western Norway and Sweden (Lindström et al. 1985; Rickard 1985; Stephens et al. 1985). A more detailed comparison with units on the mainland is beyond the scope of this paper, but is discussed in Klein (1997).

Caledonian deformation in the basement

One of the most puzzling aspects of the geology of Lofoten is the apparent lack of deformation in many of the basement rocks, which resulted in a longstanding question as to whether the Lofoten terrane was significantly involved in Caledonian orogenesis. The general lack of Caledonian deformation in the Lofoten basement is at odds with penetrative basement deformation both to the south (southwest Norway, Bryhni & Sturt 1985; Andersen & Jamtveit 1990) and to the north (S. Bergh, pers. comm. 1997), but is commonly observed along the base of the main Caledonian allochthon at the latitude of Lofoten-Ofoten (68°N) (Griffin et al. 1978; Bartley 1980, 1981, 1982; Hodges et al. 1982; Van Winkle et al. 1996). Similarly, field mapping and structural analysis on Vestvågøy have revealed structures and fabrics interpreted as Caledonian in origin on the basis of kinematic and temporal similarities with Caledonized rocks exposed on the mainland. These fabrics and structures are prevalent in the allochthonous cover rocks, and continue into the basement to depths of <1 km. Below this, deformation is concentrated in narrow (generally less than 15 m), anastomosing shear zones that may or may not be concordant with the basement–allochthon contact. Similar relations are found on Røst and Værøy (Holloman 1996; Mooney 1997). Bartley (1982) attributed the lack of significant Caledonian deformation in the basement on Hinnøy to a limited availability of water hypothetically provided by dehydration reactions during prograde metamorphism of both the overlying allochthon and the underlying cover rocks. Van Winkle et al. (1996) report that similar occurring WGR-basement shear zones in western Ofoten are concentrated along the boundaries with supracrustal xenoliths, consistent with Bartley's idea. The present authors agree that the lack of fluids in the dry, granulite–facies basement of Vestvågøy probably influenced its lack of intense Caledonian reworking away from the Leknes group contact.

Results of detailed geologic mapping on west-central Vestvågøy help to refine further the structural and metamorphic history first described by Tull (1973, 1977). Before the recognition of shear-sense indicators in mylonites (Berthé et al. 1979; Lister & Snoke 1984; Simpson 1986) and in phyllonites (Platt & Vissers 1980; Dennis & Secor 1987), most faults in collisional orogenic belts were thought to be thrust faults, in accordance with the overriding paradigm of mainly contractional stresses along collisional tectonic plate boundaries. Tull (1977) interpreted the contact between the Leknes group and the WGR as a 'tectonic slide,' the attenuated overturned limb of a fold nappe. Griffin & Taylor (1978) suggest that a similar contact on Værøy may be a Caledonian thrust. Our findings are largely in agreement with these interpretations, but the new isotopic and kinematic data support the idea that extensional movements have substantially modified this earlier contractionally developed edifice.

Effects of post-Caledonian extension

An important result of our work on Vestvågøy is the recognition of normal-slip, top-west movement along moderately northwest-dipping shear zones that appear to have reactivated the major top-east directed Leknes thrust. Top-west extension is mainly manifested in wide (ca. 1 km) ductile shear zones containing west-dipping extensional shear bands, west-verging rootless folds, and asymmetrical feldspar porphyroclasts. West-plunging, oblique-dip elongation lineations in the mylonitic foliation are interpreted to indicate the line of transport. These findings are consistent with regional $^{40}Ar/^{39}Ar$ data that support the idea that Lofoten lies in the footwall block of a major, top-west, extensional detachment (Coker et al. 1995). In addition, previously hard-to-explain, regionally developed, west-vergent orogenic backfolds (Steltenpohl & Bartley 1988) can be geographically, geometrically, kinematically, and temporally linked to top-west movements along these Lofoten shear zones (Klein 1997).

Post-Caledonian metamorphic peak structures exposed on Vestvågøy correlate well with structures exposed farther east on Hinnøy and in the Ofoten–Efjorden–Tysfjorden region of the mainland (ca. 120 km east of Vestvågøy). F_3 folds of the study area may be correlative with regional, late-phase F_3 cross-folds of Bartley (1981), Steltenpohl (1983, 1987), and Steltenpohl & Bartley (1988). The folds also correlate with the F_3 folds of Tull (1973) in that they fold S_2 and have no axial plane foliation. The F_3 folds correspond to the macroscopic F_2 folds of Gustavson (1972). F_4 folds correspond to late-phase F_4 backfolds of Steltenpohl & Bartley (1988). The D_5 breccia zone on Vestvågøy has a similar orientation to the late-stage faults described on Hinnøy (Bartley 1980), on Grytøya (Van Winkle 1994; Van Winkle et al. 1996), and in Skånland (Steltenpohl 1987) on the adjacent mainland. The absolute timing of the late-stage faulting on Vestvågøy is unclear, but similar faults throughout Lofoten and Vesterålen have been assigned Jurassic–Cretaceous ages based on offshore data (Løseth & Tveten 1996). Alternatively, Olesen et al. (1997) interpret that brittle faulting in Lofoten–Lopphavet may have initiated as early as the Permian, and that a westward shift in regional fault activity may have occurred from the Carboniferous–Permian (mainland) to the late Jurassic–early Cretaceous (outer Lofoten).

Role of the Leknes group in the tectonic evolution of the Caledonides

Results from work in Lofoten provide a clearer view of how extensional movements modified the contractional Caledonian orogen to produce the present-day attenuated margin. The initiation of extension on Vestvågøy during D_3-D_4 is interpreted to have taken place at higher crustal levels during the Devonian, synchronous with or immediately following Silurian D_2 thrusting (Klein 1997), based on $^{40}Ar/^{39}Ar$ mineral cooling dates from hornblende and muscovite reported by Hames & Andresen (1996a). On Vestvågøy, D_2 muscovites cooled rapidly through the closure temperature of ^{40}Ar (ca. 350°C) during the Devonian (390–365 Ma), based on ages obtained within 500 μm of the rim of a single muscovite prophyroblast (Hames & Andresen 1996a). Fine-grained muscovite in S_4 extensional shear zones that cross-cut S_2 yields $^{40}Ar/^{39}Ar$ ages identical to the youngest rim ages of the larger porphyroblasts (ca. 365 Ma) (Hames & Andresen 1996a), suggesting that a major phase of ductile extension occurred on Vestvågøy during the late Devonian. D_2 thrusts on Vestvågøy were reactivated during extension, probably because they acted as zones of weakness in the crust. Devonian extensional reactivation of pre-existing thrusts has been reported from the Jotunheimen area of southern Norway (Milnes & Koestler 1985) and the Nordfjord–Sogn detachment (west Norway; e.g. Osmundsen & Andersen 1994; Andersen & Jamtveit 1990). On Røst, at the southern terminus of Lofoten, cooling through 350°C took place from 315–270 Ma, some 100 million years later than on Vestvågøy (Hames & Andresen 1996a), implying a westward shift in differential uplift of the region consistent with the findings of Coker et al. (1995). Low-angle shear zones on Røst and associated unroofing of metamorphic rocks is interpreted to have been broadly contemporaneous with Permian extension elsewhere in Scandinavia (e.g. western Norway, Dalsfjord fault, Torsvik et al. 1992) (Hames & Andresen 1996a). Likewise, the transition from ductile to brittle deformation during D_4 and D_5 recorded in rocks exposed on Vestvågøy may also be contemporaneous with these Permian extensional events. Geophysical studies indicate that the crust in Lofoten is isostatically compensated to the west and east. However, the horst-like Lofoten culmination is cored by a mantle high, and bounded by deep half-grabens filled with Devonian to Cretaceous sediments (Bukovics & Ziegler 1985; Mjelde et al. 1993). Reactivation of Caledonian thrust faults by extensional movements during the middle to late Paleozoic has been postulated as an explanation for the development of half-grabens off the north coast of Scotland (Brewer & Smythe 1984; Blundell 1984).

On Vestvågøy, the sense of shear during D_3-D_4 extension is top-west with a left-slip component. The importance of this strike-slip component to the extensional movements in the Vestvågøy mylonites is not yet understood. Sinistral and dextral components are common in extensional regimes, however, and are considered to be transtensional (e.g. the late Paleozoic Alleghanian–Hercynian system, Steltenpohl et al. 1993; the Swiss Alps, Selverstone 1988; and the Chilean Cordillera, Dalziel & Brown 1989). Sinistral strike-slip motion is recorded in shear zones along the WGR basement–cover contact in Ofoten (Van Winkle 1994; Van Winkle et al. 1996), ca. 130 km northeast of the study area. Van Winkle (1994) and Van Winkle et al. (1996) suggest that the shear zones might lie on the cratonward side of a Devonian extensional basin, much like those in southwest Norway that are bounded laterally by major oblique strike-slip faults with opposing senses-of-shear (Andersen & Jamtveit 1990). The fabrics and structures exposed on Vestvågøy are interpreted to represent a continuation of the kinematic plan becoming recognized in Ofoten. Similarly, the half-grabens that bound the Lofoten ridge (Mjelde et al. 1993; Bukovics & Ziegler 1985) may partly have initiated from these transtensional movements. Recent papers, however, suggest that the majority of brittle faulting along the continental margin at this latitude (68°N) took place much later, in the Permian (Olesen et al. 1997) and in the Jurassic–Cretaceous (Løseth & Tveten 1996).

Late- to post-Caledonian ductile extension in Lofoten is concentrated along the basement–allochthon contact, and overprinting brittle-on-ductile relationships reflect progressive unroofing of extensional shears to shallower crustal levels during post-M_2 exhumation of the Caledonian metamorphic core. The region experienced pulses of rapid uplift and ductile extension that young to the west, suggested by diachronous mineral cooling ages sampled from the east (Vestvågøy) to the west (Røst) (Hames & Andresen 1996a). Late-Paleozoic ductile extension in Lofoten is estimated to have been of a smaller magnitude relative to the southern WGR due to the continuity of lithologies, metamorphic grade, and structural style across the extensional shear zones. As a result, we interpret that early phases of ductile extension in Lofoten were accommodated along a series of west-dipping shear zones rather than on one or two major detachments, as was the case in the southern WGR.

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