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The Silurian to Permian history of a metamorphic core complex in Lofoten, northern Scandinavian Caledonides

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[1] The Lofoten archipelago exposes Precambrian Baltic basement and Caledonian allochthonous sequences within a 1000 km long chain of gravity and magnetic highs and structural culminations along the extended, British and Norwegian continental shelf. Previous regional geophysical studies indicate that post-Caledonian extension and development of the northern Norwegian shelf occurred during broadly defined Carboniferous-Permian, Cretaceous-Jurassic, and early Tertiary events. Structures related to these events are known to young westward. We report field, structural, and ^{40}Ar/^{39}Ar thermochronologic data from rocks exposed in Lofoten that further define the history and style of post-Caledonian extension. The islands of southwest Lofoten also represent the most outboard exposures of Caledonian basement in northern Norway that presumably formed the middle to deep crustal core of the orogen. Metasedimentary rocks and penetratively deformed basement in Lofoten record high-grade Silurian-Devonian metamorphism and top-to-the-east (hereinafter tops-east) thrusting followed by episodes of Late Devonian to Early Carboniferous, tops-west, ductile extension which progressed into oblique left-slip movements. The structural style and timing of Silurian contraction in this area are remarkably similar to that determined for the more forelandward areas on the mainland, ~120 km to the east, supporting the inference that distal parts of the Baltic continental margin that were once deeply subducted are presently exposed in Lofoten. The timings of post-Devonian structural events that affected rocks in Lofoten are partially constrained by the ages of unconformities and strata known to be preserved in graben flanking the Lofoten culmination. The radiometric age and structural data presented in this study, in combination with stratigraphic constraints, suggest a westward progression through time of extensional deformation over a protracted interval of Silurian to Permian time. The latest, Permian extension in Lofoten is largely characterized by brittle structures that formed at conditions substantially less than 300°C. Compared to the exhumation history of the southern Western Gneiss Region, the depth of Caledonian, continental (A-type) subduction and subsequent unroofing of Lofoten are of lesser magnitude, and the present erosional level remained in the middle crust for a much longer interval of time. The Permian ^{40}Ar/^{39}Ar mineral ages documented in this study are the youngest such ages yet identified in Scandinavia. These ages relate to episodes of deformation and cooling in response to extensional tectonic events that occurred roughly 100 m.y. after comparable effects identified on the Caledonian mainland. Our preferred explanation for the Carboniferous-Permian radiometric ages, structural evolution, and stratigraphic data for Lofoten is that they all developed in the context of a long-lived Cordilleran-style metamorphic core complex. *INDEX TERMS:* 8105 Tectonophysics: Continental margins and sedimentary basins (1212); 8110 Tectonophysics: Continental tectonics—general (0905); 8115 Tectonophysics: Core processes (1507); 9335 Information Related to Geographic Region: Europe; *KEYWORDS:* Norwegian shelf, Caledonides, Lofoten, extension, Permian. **Citation:** Steltenpohl, M. G., W. E. Hames, and A. Andresen (2004), The Silurian to Permian history of a metamorphic core complex in Lofoten, northern Scandinavian Caledonides, *Tectonics*, *23*, TC1002, doi:10.1029/2003TC001522.

1. Introduction

[2] The Lofoten islands (Figure 1) are historically enigmatic features with regard to models of Caledonian tectonics. These islands form part of the Western Gneiss Region (WGR), which is considered to be the western margin of the ancient Baltic craton. Caledonian evolution involved partial westward subduction of Baltica beneath Laurentia [*Hodges et al.*, 1982; *Andersen and Jamtveit*, 1990; *Dewey et al.*, 1993]. Discovery of Silurian ultrahigh-pressure metamorphic assemblages in the southern WGR have partially verified this model. However, high-pressure metamorphism of basement gneisses in northern East Greenland [*Gilotti*, 1993] indicates there was also significant eastward subduction of Laurentia beneath Baltica. The geology of

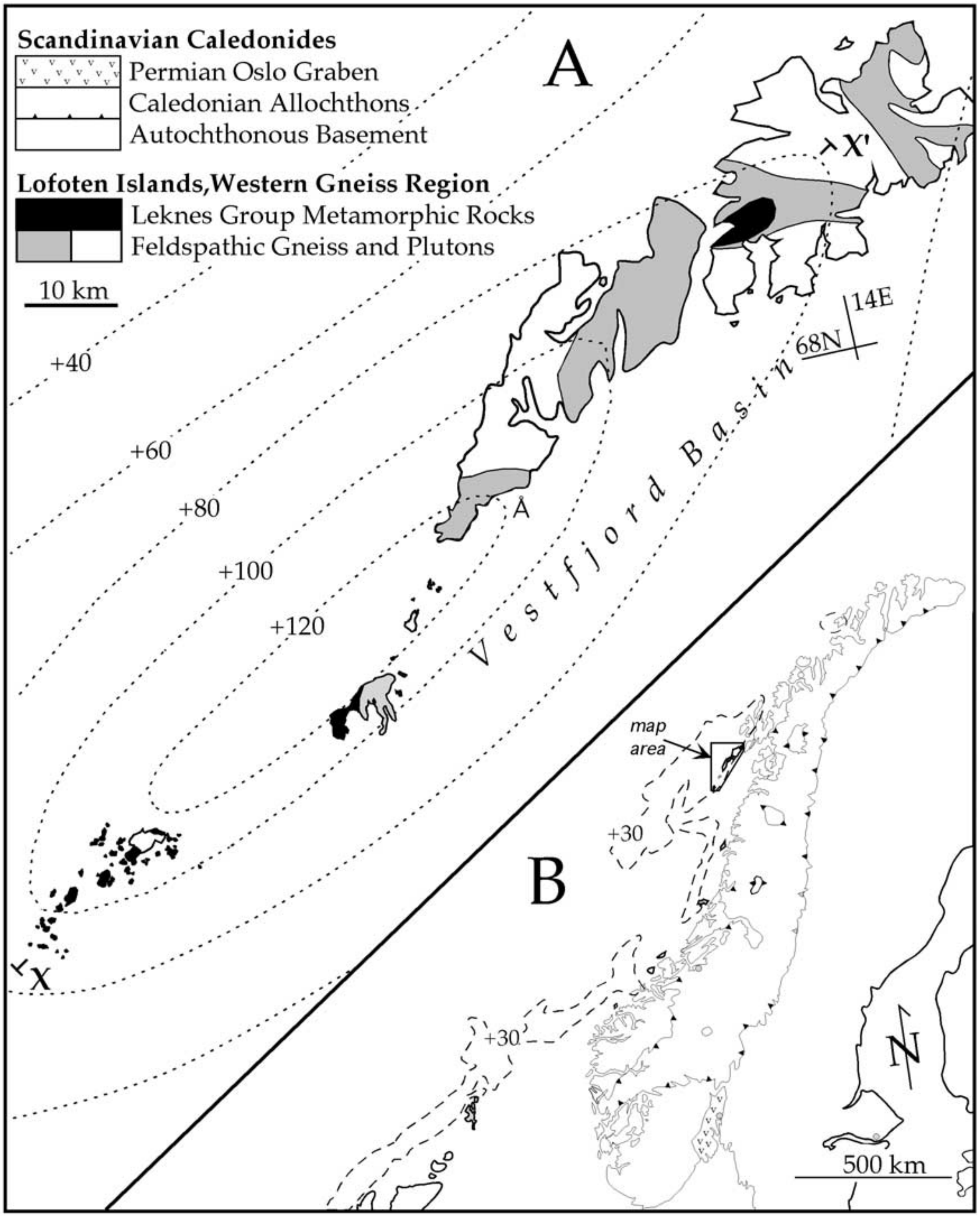


Figure 1. Location map with localities and regional Bouguer gravity gradient [from *Hames and Andresen*, 1996].

Lofoten, moreover, has been difficult to integrate with these models of continental subduction because previous studies indicated an almost complete lack of Caledonian effects in Lofoten [e.g., *Hakkinen*, 1977; *Griffen et al.*, 1978; *Tull*, 1978; *Bartley*, 1982a, 1984]. *Talwani and Eldholm* [1977] and *Tull* [1977] suggested that the Lofoten terrane may be a tectonic window beneath the Caledonian allochthons, noting that this does not simply account for the lack of a Caledonian overprint. Later, various models, including suturing of a microcontinent onto coastal Baltica, were suggested to accommodate a supposed high-crustal level for the Lofoten terrane throughout the Caledonian orogeny [e.g., *Hakkinen*, 1977; *Griffen and Taylor*, 1978; *Griffen et al.*, 1978; *Tull*, 1978]. Today, it generally is accepted that the WGR in Lofoten is continuous with the Baltic basement of the foreland and that the weak Caledonian effects are the

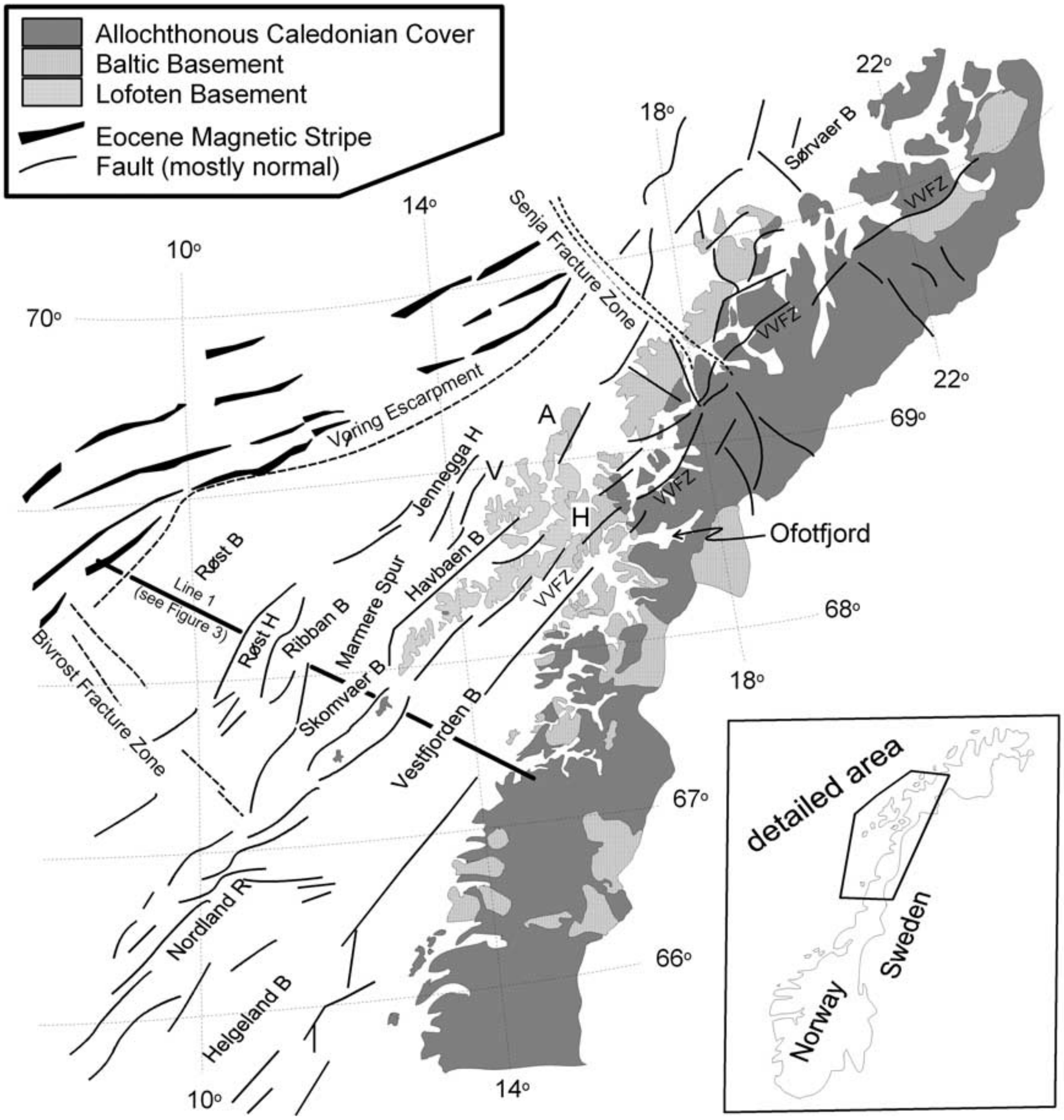


Figure 2. Main structural elements related to Norwegian margin development in the Lofoten and broader region (modified from *Olesen et al.* [1997]). A, Andøya; B, basin; H, Hinnøy; R, ridge; VVFZ, Vestfjord-Vanna fault complex. Line 1 is the trace of cross section in Figure 3.

result of a lack of fluids in the dry, granulite-facies Baltic crust [*Bartley*, 1982a, 1984; *Hodges et al.*, 1982; *Olesen et al.*, 1997]. *Hames and Andresen* [1996] reported initial findings of ^{40}Ar/^{39}Ar mineral cooling data that documented Caledonian metamorphism and deformation in parts of southwest Lofoten. Herein, we report additional ^{40}Ar/^{39}Ar data as well as detailed field and structural observations that help to clarify the Caledonian evolution of Lofoten.

[3] An unexpected finding is that rocks in southwest Lofoten record a rich history of post-Caledonian extension. The tectonic evolution that can be traced through data presented in this paper has important implications for an understanding of the north Norwegian margin. The petroleum potential and recent exploration of the northern Norwegian shelf (Figure 2) has led to the proliferation of geophysical and drill core data from this region. Our field and laboratory studies, combined with the reported geophysical data, can be used to trace the extensional modification of midcrustal level, late Caledonian (Early Devonian), extensional structures through early Tertiary continental separation. We have discovered that some prominent pervasive, crystal-plastic and brittle structures and fabrics in southwest Lofoten formed as a result of a significant Permian extension event. Although upper crustal, brittle Permian extensional structures are known to have reactivated the Dalsfjord fault in the southern WGR [*Torsvik et al.*, 1992] and formed the Oslo rift [*Neuman et al.*, 1992], it appears that Lofoten contains the only crystal-plastic, middle crustal remnants of this event available for surface study.

[4] In addition to their important role as hydrocarbon traps, extensional structures along the southwest Norwegian margin have proven important to models of extensional tectonics and continental margin evolution. Studies of the Devonian basins and associated basement-cover contacts in southwest Norway have strongly influenced our understanding of the style and extreme magnitude of extension that took place along this evolving continental margin [*Norton*, 1986; *Andersen and Jamtveit*, 1990; *Andersen et al.*, 1991]. Extensional faults bounding the basins juxtapose unmetamorphosed Devonian sediments upon Precambrian basement rocks that were metamorphosed to form coesite- and diamond-bearing eclogites during the Late Silurian [*Norton*, 1986; *Andersen et al.*, 1991]. Though this juxtaposition was partly controlled by late Paleozoic and Mesozoic faulting [*Torsvik et al.*, 1992], it provides a compelling example of how the deep crust is tectonically exhumed during gravitational collapse [*Andersen et al.*, 1991]. Recent studies in the East Greenland Caledonides [e.g., *Hartz and Andresen*, 1995] provide a basis for comparing extensional tectonic development on opposite sides of the orogen. In north Norway, however, the magnitude and style of Devonian and subsequent extension is relatively little explored and the subject of debate [*Steltenpohl and Bartley*, 1993; *Fossen and Rykkelid*, 1993; *Coker et al.*, 1995; *Northrup*, 1996; *Klein et al.*, 1999]. Our results document the style of Silurian-Devonian contraction and subsequent extension in Lofoten and aid correlations of these events throughout the Caledonides.

2. Geologic Setting

[5] The Scandinavian Caledonides comprise a variety of vertically stacked nappes thrust from west to east on to the Baltoscandian margin as it was partially subducted beneath Laurentia during the early to middle Paleozoic [*Gee*, 1975; *Roberts and Gee*, 1985; *Hodges et al.*, 1982]. A belt of gravity and magnetic highs and structural culminations within the continental shelf of Europe extends from Britain to northern Norway, roughly parallel to the trend of the Caledonides (Figure 1). The Lofoten archipelago provides exposures of this belt and the most internal exposures of the north Norwegian margin. Rocks in Lofoten (Figure 1) occur in two tectonic settings: (1) allochthonous, amphibolite-facies, metasedimentary cover rocks informally known as the "Leknes group" [*Tull*, 1978; *Sigmond et al.*, 1984], which are in thrust contact with; (2) granulite-facies Archean-Proterozoic gneisses and granitic plutons typical of the WGR [*Griffin et al.*, 1978].

[6] Geophysical and drilling studies indicate that three major phases of post-Caledonian extension affected the submerged and buried units in the vicinity of Lofoten: (1) Carboniferous-Permian brittle faulting and half-graben formation; (2) Cretaceous-Jurassic brittle faulting and half-graben formation; and (3) early Tertiary continental separation and initial formation of oceanic crust within the North Atlantic basin. *Olesen et al.* [1997] document a general westward younging of onshore and offshore brittle faults and other structures in the Troms-Ofoten-Lofoten region. Data bearing on the evolution of brittle structures in the large area between Lofoten and Finnmark (i.e., the Vestfjorden-Vanna fault complex) in previous compilations is relatively limited (e.g., the study of *Olesen et al.* [1997] is mostly based on a thesis by *Forslund* [1988] for this region). In addition to such earlier studies, the present investigation summarizes observations of late and brittle structures in the Lofoten-Ofoten region from *Steltenpohl* [1987] for western Ofoten; *Van Winkle et al.* [1996] for north of Harstad; *Klein and Steltenpohl* [1999] for Vestvågøy; *Klein et al.* [1999] for Lofoten; *Mooney* [1997] for Værøy; *Holloman* [1996] Røst; and *Waltman* [1997] for Lofoten.

[7] Figure 3 is an idealized cross section across the north Norwegian margin that corresponds to "line 1" on Figure 2. The northwestern and central parts of this cross section are based on two separate seismic reflection models. The northwestern part, from the edge of the section to the Røst High, is from *Mjelde et al.* [1996] and the central part, from the Røst High to the center of Vestfjorden basin, is from *Mjelde et al.* [1993]. The southern continuation of the cross section to the mainland is based on our extrapolation of these geophysical data with the known surface geology. Latest Paleozoic and, mainly, Tertiary extension controls the style of the cross section, and the major extensional faults are indicated. Bouguer gravity anomalies along the Lofoten Ridge are correlated with variations in crustal thickness. Crust is isostatically compensated to the west and east of Lofoten. The horst-like Lofoten culmination, however, is uncompensated and cored by a high-density zone of presumed mantle material and is bounded by deep half grabens with presumed Devonian to Cretaceous sediments [*Mjelde et al.*, 1993; *Bukovics and Ziegler*, 1985].

3. Structural Geology of Southwest Lofoten

[8] Field studies were done on islands of southwestern Lofoten where allochthonous Caledonian metasedimentary rocks are exposed: Vestvågøy, Værøy, and many islands within the Røst archipelago (see Figures 1 and 4). Comparison of lithologies and structures between these islands and the adjacent Ofoten mainland (named for the large Ofotfjord; Figure 2) is complicated by intervening expanses of undeformed Precambrian crystalline basement and submerged regions. However, the extreme westward exposures afforded by these islands are well suited to make such a comparison, test the hypothesis that the northern WGR is a partially subducted segment of Baltic basement, and provide additional information bearing on the regional Paleozoic tectonic evolution. Below, we discuss structural observations made on rocks from each of these islands, starting in the northeast and working to the southwest. The structural sequences established for each of these island study areas, and that reported on the mainland in Ofoten, are reported for comparison in Table 1.

3.1. Leknes, Vestvågøy

[9] The overall structure of the Leknes area on Vestvågøy is dominated by the shallow, W-NW plunging Leknes synform [*Tull*, 1978] and cross cutting late stage brittle

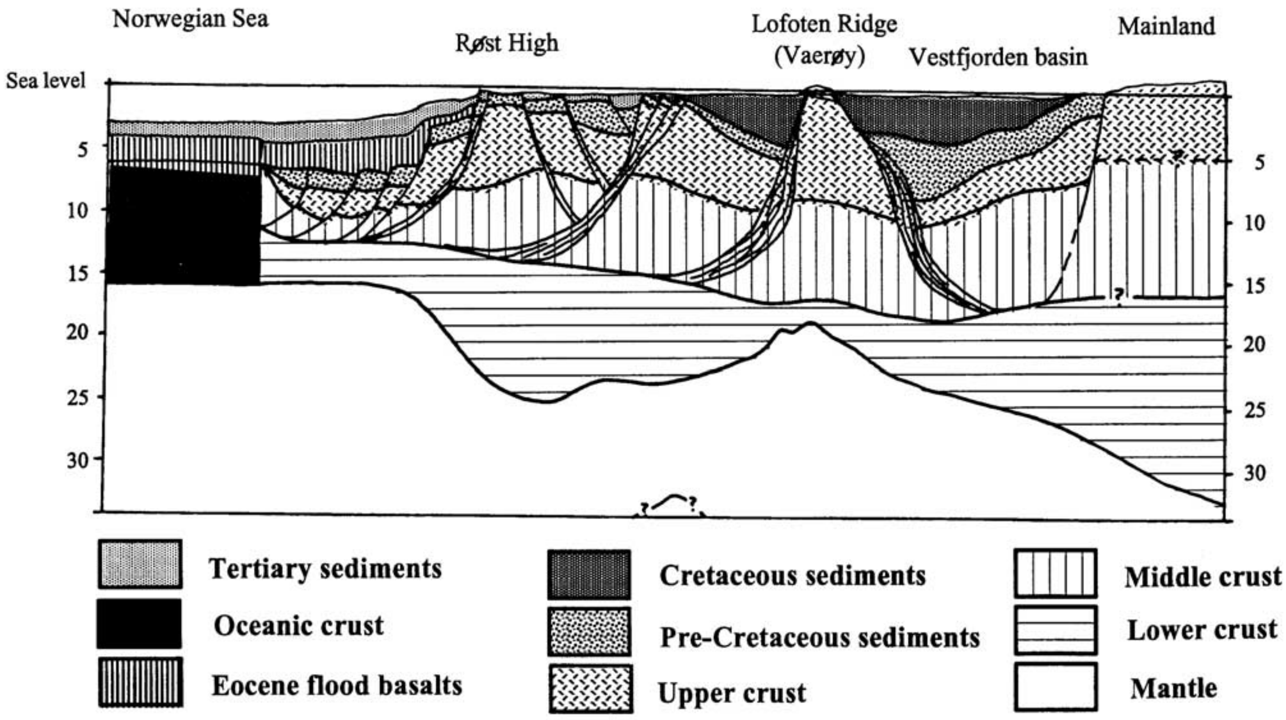


Figure 3. Idealized cross section across the modern Norwegian margin in the Lofoten region (see line 1, Figure 2 for location). See text for explanation.

faults (Figure 4a). The general tectonostratigraphic sequence, from bottom to top, comprises Archean mangeritic basement rocks structurally overlain by metasedimentary rocks of the Leknes group [*Tull*, 1978]. The Leknes group contains, from bottom to top, a lower sequence of laminated amphibolite with thin quartzite and calcite marble, muscovite-kyanite schist, quartzofeldspathic mica schist, and an upper laminated amphibolite and quartzite [*Tull*, 1978; *Klein*, 1997; *Klein and Steltenpohl*, 1999; *Klein et al.*, 1999].

[10] Metamorphism of the Leknes group attained kyanite zone conditions during formation of the primary schistosity and gneissosity (S_2, Table 1). Elemental partitioning thermobarometry on garnet-kyanite-plagioclase-biotite-muscovite assemblages with retrograde staurolite in samples of Leknes group schists document equilibrium pressure-temperature ranges of 7.6–9.2 kbar and 560–660°C [*Mooney*, 1997], which are consistent with petrogenetic grids for such pelitic rocks [e.g., *Spear and Cheney*, 1989]. The $^{40}Ar/^{39}Ar$ data of *Hames and Andresen* [1996] indicate the Leknes group experienced kyanite-grade metamorphism and cooling over the interval 425–365 Ma.

[11] Several tops-east D_2 thrust faults imbricate and repeat parts of the Leknes group, including slivers of mylonitized granitic rock interpreted to be deformed basement [*Klein*, 1997; *Klein and Steltenpohl*, 1999; *Klein et al.*, 1999]. Microstructural studies indicate that mylonites from these thrusts formed under synmetamorphic (kyanite zone) conditions. The lack of intracrystalline strain features in D_2 mylonites of the Leknes group of Vestvågøy indicates annealing and near complete recovery, which is identical to the style of D_2 Caledonian thrust zones of the Ofoten region [*Hodges et al.*, 1982; *Bartley*, 1984; *Hodges*, 1985; *Steltenpohl*, 1987; *Northrup*, 1996] (see Figures 5a and 5b). However, younger brittle structures and chlorite-grade retrogressive assemblages locally overprint the earlier, higher-grade fabrics [*Klein*, 1997] (see Figures 5c and 5d). Tops-east thrusting is indicated by a consistent, downdip elongation lineation (L_2, Figure 6) combined with S-C fabrics, sigma-type porphyroclasts, normal- and reverse-slip crenulations [*Dennis and Secor*, 1987], and lattice-preferred orientation (LPO) in quartz. All observations are consistent with tops-S65°E emplacement of nappes (Figure 4a), practically identical to that documented on the mainland to the east [*Coker et al.*, 1995]. The Leknes synform is interpreted to have formed as a result of D_2 movements [*Tull*, 1977; *Klein*, 1997]. As in western Ofoten, mylonitic fabrics associated with the basal Caledonian thrust in Leknes decrease and gradually disappear structurally downward into the Baltic basement over an interval of less than 250 m.

[12] A set of NW-SE trending cross folds, with axes oriented at a high angle to the orogenic structural grain, formed during D_3. These folds are identical in practically all regards to the D_3 crossfolds described in western Ofoten by *Steltenpohl and Bartley* [1988]. The folds generally contain no axial planar fabric. Structural analysis indicates that they overlapped with late D_2, and formed prior to or synchronously with D_4, described below. The D_3 cross folds are interpreted to record NE-SW, orogen-parallel contraction.

[13] Tops-west, D_4 extensional shears locally have overprinted S_2 as well as the D_2 mylonites in the southern parts

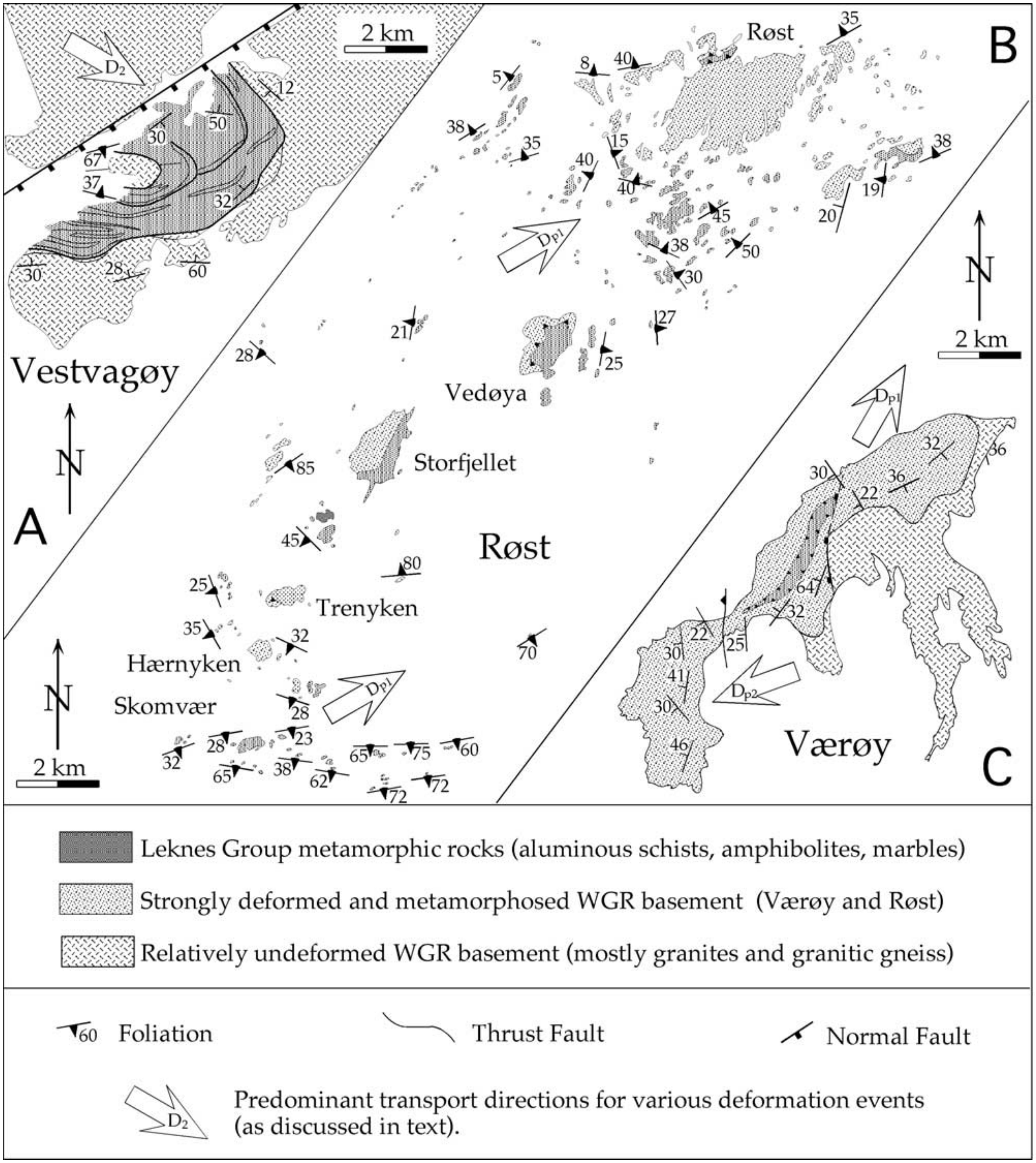


Figure 4. Geologic maps of the (a) Leknes (Vestvågøy), (b) Røst, and (c) Værøy areas. *Holloman* [1996], *Klein* [1997], *Mooney* [1997], and *Waltman* [1997] mapped the geology of these areas.

of the Leknes study area. These retrogressive, greenschist-facies shears are zones of accumulated noncoaxial simple shear concentrated along earlier formed, synmetamorphic (kyanite zone), D_2 thrusts and within the upper parts of the basement complex for approximately 250 m beneath the basement-cover thrust. Tops-west-normal-and-oblique-left-slip movement along these shear zones is documented by S-C fabrics, sigma-type porphyroclasts, normal- and reverse-slip crenulations, and LPO in quartz [*Klein*, 1997]. The D_2 thrusts and deformational fabrics clearly have been reactivated during later tops-west D_4 movements (Figures 5c and 5d). F_4 backfolds, well known from studies

Table 1. Correlations of Structural and Metamorphic Events in Lofoten, Norway[a]

Western Ofoten	Vestvågøy	Værøy and Røst
Tull et al. [1985] and *Steltenpohl and Bartley* [1988]	*Tull* [1978] and *Klein* [1997]	*Mooney* [1997] and *Waltman* [1997]
D_1, prekyanite-grade assemblage preserved as inclusion trails in D_2 garnet, staurolite, and kyanite porphyroblasts, S1 in basement (?)	D_1, prekyanite-grade assemblage preserved as inclusion trails in D_2 garnet porphyroblasts, S_1 in basement(?)	D_1, basement shear zones, prekyanite-grade assemblage in cover rocks, S_1 in shear zones in basement, L_1 mineral lineation
D_2, synkyanite-grade event, most pervasive, tight to isoclinal folds, S_2 schistosity/gneissosity, L_2 mineral lineation, synmetamorphic mylonite zones, tops-E-SE thrusting	D_2, synkyanite-grade event, most pervasive, tight to isoclinal folds, S_2 schistosity/gneissosity, L_2 mineral lineation, synmetamorphic to upper greenschist facies mylonite zones, tops-S65°E thrusting	D_2, synkyanite-grade event, evidence is largely obliterated by later events
D_3, postpeak metamorphic NW-SE cross folds, open kink and chevron styles, rare axial planar greenschist-facies fabric, NE-SW contraction	D_3, transitional greenschist and amphibolite facies, overlapped with late D_2, NW-SE cross folds, no axial planar fabric, NE-SW contraction	mostly obliterated by later events
D_4, overlapped with D_3, NE-SW trending, NW verging backfolds, retrogressive mylonite zones, L_4 elongation lineation, lower amphibolite-to-lower greenschist-facies conditions, tops-west and oblique left-slip shearing	D_4, overlapped with D_3, NE-SW trending, NW verging backfolds, S_4 retrogressive mylonites, L_4 elongation lineation, amphibolite-to-lower greenschist-facies conditions, tops-west and oblique left slip shearing	mostly obliterated by later events
D_5, brittle faults	D_5, brittle faults	D_{P1}, most pervasive event, retrogressive greenschist-facies S_{P1} mylonitic foliation, approximately N50°W, 10–20° SW, L_{P1} elongation lineation, plunges ~10–20°, S50°W, tops-northeast, large F_{P1} recumbent sheath folds D_{P2}, retrogressive greenschist-facies S_{P2} mylonitic foliation, approximately N50°W, 10–20° SW, L_{P2} elongation lineation, plunges ~10–20°, S40°W, tops-west D_{P3}, brittle faults, fracture cleavage, fractures, hydrothermal muscovite growth on Værøy

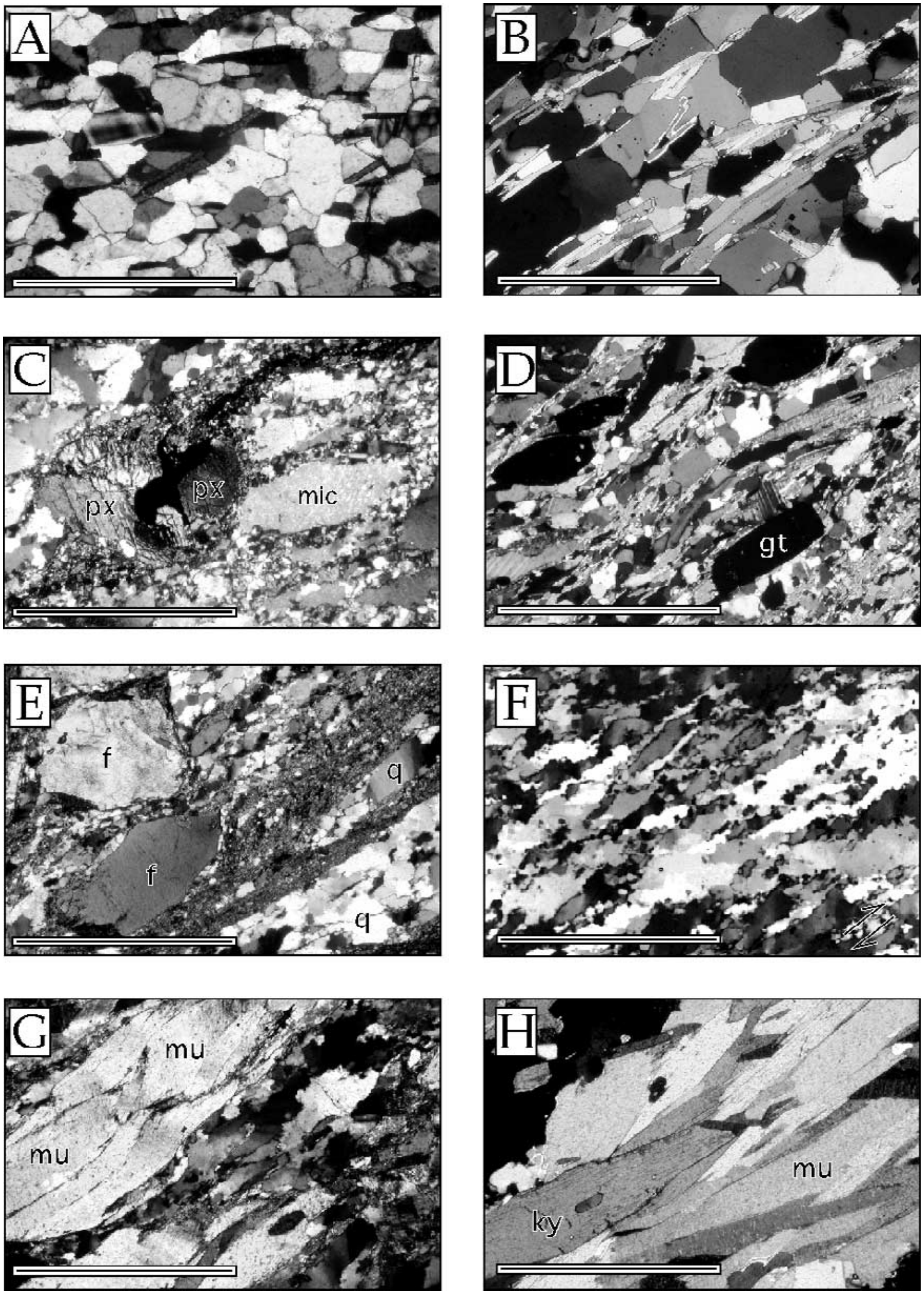
[a]Structural elements produced during a deformational event are numbered the same; for example, S_1 and L_1 formed during D_1, and S_2 and L_2 formed during D_2, etc.

in the adjacent mainland Caledonides [*Steltenpohl and Bartley*, 1988, and references therein], are rootless folds that refold earlier formed folds and fabrics and corroborate tops-west directed extension during D_4.

[14] The Leknes group and the F_2 Leknes synform are excised toward the northwest by a major, subvertical, ~0.5 km wide, brecciated and silicified brittle fault zone (D_5) [*Klein*, 1997]. This fault clearly truncates D_4 structures and the basement-cover contact. Breccias contain clasts of mylonitized granitic basement rock that are cut by veins of, and cemented together by, very fine-grained, dark purple, hematite-rich material and calcite [*Klein et al.*, 1999]. Some thin (<5 mm thick), darker colored veins within the country rock may be pseudotachylites. This brittle fault continues southwestward beneath the fjord between Vestvågøy and Flakstadøy and is exposed as numerous dispersed brittle shear zones within mangeritic orthogneiss on east Flakstadøy. Although sense of movement within the cataclasites was indeterminate, a minimum of 2 km of tops-southeast, normal-slip separation is estimated based on displacement of the F_2 Leknes synformal axis. This F_2 axis, delineated by the synformal fold of the basement-cover contact, has been elevated to some unknown level above the present-day outcrop surface of the local mountain peaks of the footwall (northwest) block (see Figure 4), which are wholly underlain by mangerite of the basement complex. Movement along this fault postdated the Silurian D_2 event because it clearly cuts D_2 structures and fabrics. Locally, F_3 folds appear to be either cut by the fault [*Klein*, 1997] or formed synchronously with it. Presumably it formed as a result of post-Devonian extension.

3.2. Værøy

[15] The overall structure of Værøy is that of a single panel of strongly mylonitized, shallow dipping, metasedimentary cover rocks resting upon weakly to undeformed mangeritic basement along a well-developed retrogressive mylonitic shear zone. A major, steeply dipping, N-S trending, tops-west extensional shear zone cuts the island roughly in half, and has down dropped Caledonian metasedimentary rocks adjacent to uplifted basement rocks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(Figure 4c). The main foliation, here a retrogressive greenschist-facies mylonitic foliation, dips gently toward the southwest on the southern half of the island but on the northeastern end it is subhorizontal and locally dips toward the east.

[16] Metasedimentary rocks on Værøy consist mainly of aluminous schists (locally containing the assemblage garnet-biotite ± staurolite ± kyanite), thin layers of quartzite, and an underlying garnet-amphibolite [*Mooney*, 1997; *Waltman*, 1997]. The Værøy basement is mostly composed of undeformed mangerite that becomes progressively mylonitized within ~500 m of the basement/cover contact. *Mooney* [1997] interpreted the metasedimentary units and intercalated amphibolite to lithologically correlate with the Leknes group on Vestvågøy, and, consequently, herein we include them with the Leknes group. The ^{40}Ar/^{39}Ar data presented by *Hames and Andresen* [1996], and additional data discussed below, indicate the retrogressive mylonitic and cataclastic structures on Værøy resulted from Permian deformation. In the present study, for convenience, the Permian structural/fabric elements are denoted using the upper case "P" subscript. Thus Permian S_{P1} retrogressive mylonites formed during D_{P1} extension.

[17] Retrogressive mylonites predominate the cover and adjacent basement rocks on Værøy and contrast sharply with the annealed and recrystallized D_2 deformational microstructures preserved in rocks on Vestvågøy and in western Ofoten. The S_2 metamorphic foliation on Værøy, which is interpreted to correlate to S_2 on Vestvågøy, has been largely destroyed due to retrograde mylonitization. Locally, S_2 is preserved in the hinge zones of intrafolial isoclinal folds, the limbs of which are parallel to the $S_{P1,}$ retrogressive mylonitic foliation (Figure 7a). S_2 is also infered to be preserved as inclusion trails evident within porphyroclasts of garnet, staurolite, and kyanite [*Mooney*, 1997] that are prekinematic with respect to a surrounding S_{P1} mylonitic matrix. Mylonitization is concentrated along the basement-cover contact, which is a major tops-northeast ductile shear zone. Microstructural development of the retrogressive mylonites from this shear zone (Figures 5e and 5f) indicates formation under conditions ranging from the upper (crystal-plastic deformation in plagioclase) to the lower (crystal-plastic deformation in quartz and crystal-brittle feldspar) greenschist facies. Tops-northeast movement along these shear zones is indicated by a consistent, downdip elongation lineation (Figure 6) combined with S-C fabrics, sigma-and-delta-type porphyroclasts, normal- and reverse-slip crenulations, microfolds, and strong LPO in quartz. All observations are consistent with tops-northeast (N40°E) ductile shearing (Figure 4b). Mylonitic transport on Værøy, therefore, roughly parallels the trend of the Lofoten islands and is nearly perpendicular to the earlier formed Caledonian thrust sliplines determined for D_2 structures in Vestvågøy (Figure 4a) and western Ofoten.

[18] A set of tight, large-scale (amplitudes up to several hundred meters and half wavelengths about 50 m), SW plunging recumbent folds (Figure 7b), F_{P1}, in mylonitized rocks within and directly beneath the basement-cover shear zone is assigned to the D_{P1} event. These folds, first reported by *Griffen and Taylor* [1978], are spectacularly displayed in cliff faces on the northwest side of Værøy (near the east side of the airfield) and near the beach at Sanden (Figures 7b). Observations from the hinge zones of these folds document that these structures (1) fold the S_{P1} mylonitic foliation, (2) root into S_{P1}, (3) have an axial planar mylonitic foliation with microstructures that are identical to those defining $S_{P1,}$ and (4) have sheath fold forms [*Cobbold and Quinuis*, 1980]. These folds therefore formed during later stages of continued movement along the basement-cover shear zone. Sense of vergence of observed F_{P1} folds was mainly tops-southwest (Figure 7b) but tops-northeast vergence was also noted. The measured fold hinges parallel the L_{P1} elongation lineation (Figure 6). Although these folds are spectacular, they are interpreted to be sheath folds and we place little confidence in their vergence having much significance for the kinematics of the D_{P1} event. Their style, scale, and position beneath what we interpret to be an extensional detachment fault (see below), however, is

Figure 5. Photomicrographs representative of rock textures found in shear zones that occur within and between granitic basement lithologies and the pelitic, allochtohonous cover of the Ofoten-Vesteralen-Lofoten region. (Each photomicrograph was taken with cross-polarized illumination, and the scale bar is 1.0 mm long.) (a) Deformed and metamorphosed basement granite from Ofoten, collected 50 m beneath the contact with the Ningen Nappe Complex. (b) Schist collected from the basal shear zone of the Ningen Nappe Complex. Note that in Figures 5a and 5b, grains of quartz, micas, and feldspar generally are equant, have straight boundaries, and lack evidence of intracrystalline strain (e.g., undulose extinction, subgrains); such textures are typical of the Ofoten region (compare to Figure 7D of *Bartley* [1982a] and see descriptions by *Steltenpohl and Bartley* [1987]). (c) Mylonitic mangerite gneiss of Vestvagøy, Lofoten, collected from a 10 m wide shear zone near the contact with the Leknes Group. Asymmetric porphyroclasts of pyroxene (px) and microcline (mic) are fractured and exhibit undulose extinction and are surrounded by a finer-grained, recrystallized matrix of amphibole, microcline, and quartz. (d) Kyanite-muscovite-garnet schist of the Leknes group. The foliation is defined by relatively finely grained, recrystallized muscovite and elongate grains of quartz and garnet (gt). (e) Mylonitic granodiorite from the basement on Værøy, 30 m below a shear zone and contact with allochthonous schists and gneisses. Note the porphyroclasts of fractured, undulose quartz (q) and feldspar (f), surrounded by a "paste" of fine-grained phyllosilicates (mostly biotite) and inequant quartz grains with sutured grain boundaries. (f) Mylonitic quartz textures in a sample collected from a10 m thick quartzite that occurs in a major shear zone on Værøy. (The sense of displacement in E and F is top-to-the-east; right in photomicrograph.) (g) Deformed muscovite (mu) in mylonitic gneiss from a shear zone on Røst, with characteristic undulose extinction, kinking, and recrystallization along grain boundaries. (h) Coarse, undeformed kyanite (ky) and muscovite from gneisses characteristic of islands around Skomvær, southwesternmost Lofoten.

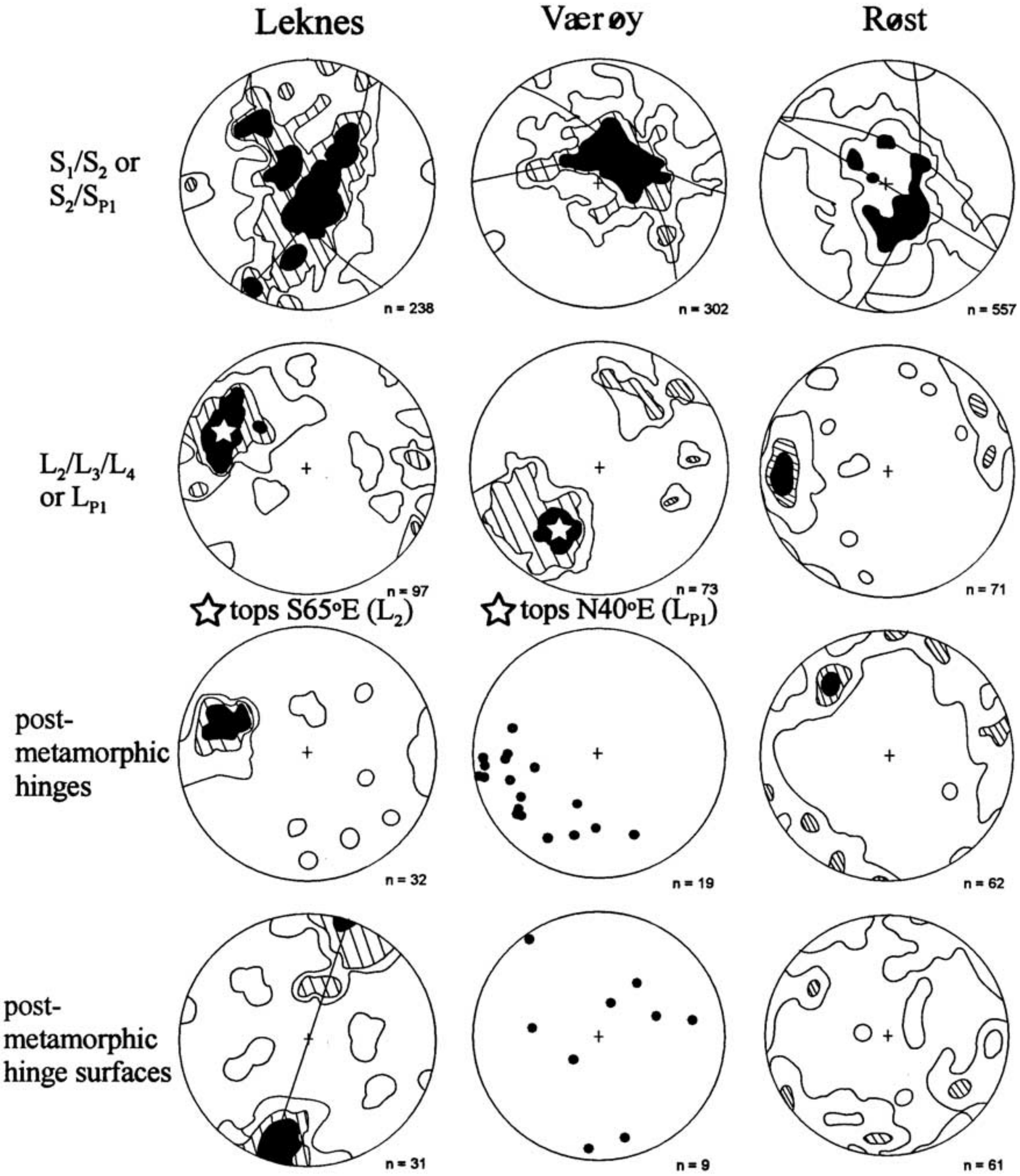

Figure 6. Lower hemisphere stereographic projections of structures and fabrics measured in the Leknes (Vestvågøy), Værøy, and Røst areas. Contour densities are 0–4%, 4–9% (lined pattern), and >9% (black) per percent area.

similar to folds developed beneath the detachment in the Ruby Mountains, Nevada, and other metamorphic core complexes [*MacCready et al.*, 1997].

[19] Locally, tops-west, D_{P2}, shear zones cut across and extend the S_{P1} mylonitic shear zones on Værøy (Figure 7c). D_{P2} shear zones are relatively thin (generally <1 m thick), distributed zones. Some are spatially associated with S_{P1} shear zones where competency contrasts existed, particularly near contacts with amphibolite boudins or layers, implying that some D_{P2} may actually be antithetic D_{P1} shears. However, a major, steeply dipping, N-S trending, tops-west, D_{P2} extensional shear zone was documented to cut the basement-cover shear zone (Figure 4). Flat-lying S_{P1} mylonites in the crests of mountain peaks on the northeast end of Værøy correspond to the shear zone along the basement-cover contact in central Værøy. Cross sections drawn across this major D_{P2} shear zone indicate approximately 250 m of normal-slip separation of the S_{P1} base-

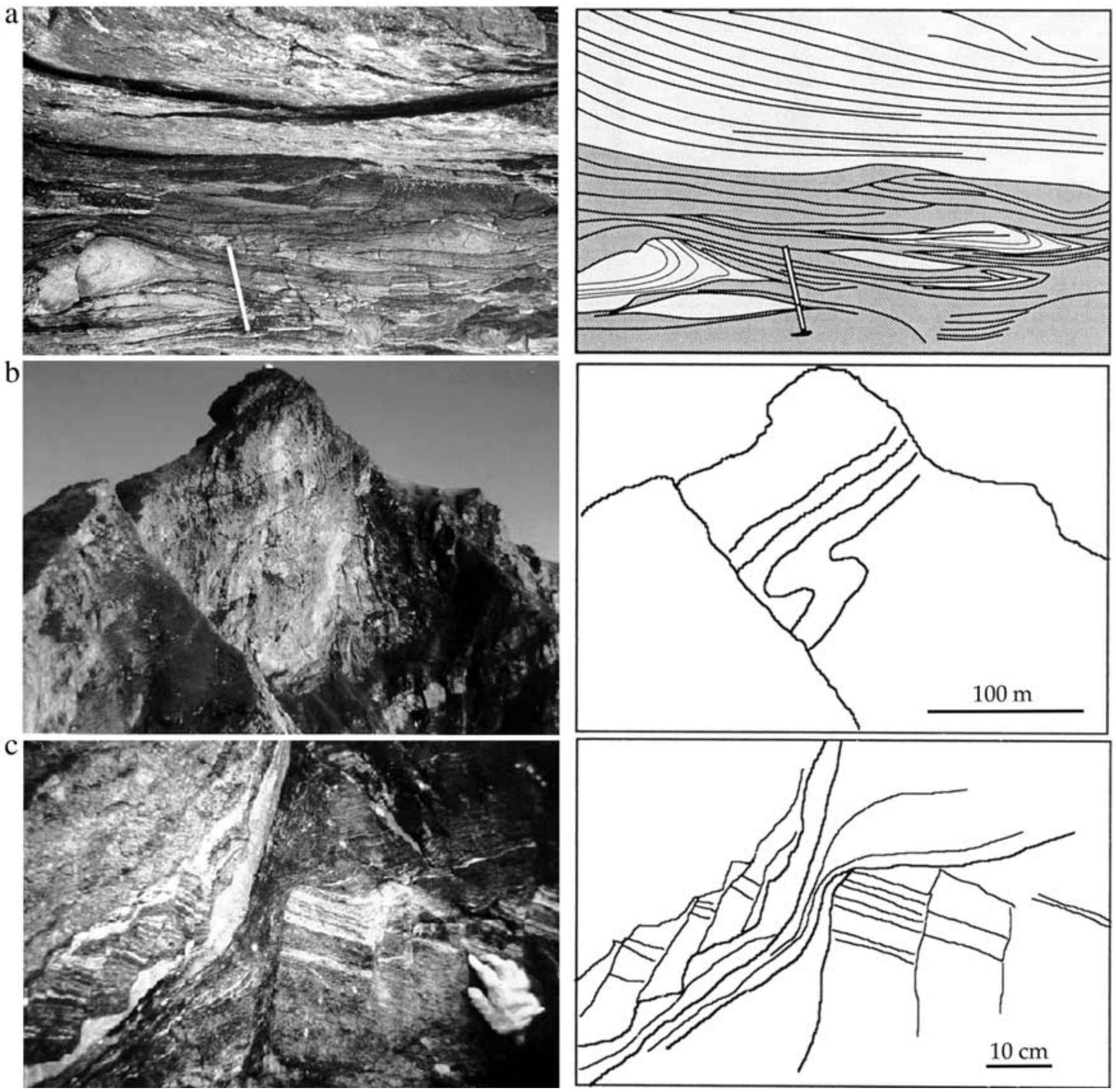

Figure 7. (a) Rare fold noses of S_2 fabric that are truncated and transposed along S_{P1} mylonitic shear zones, Røst (hammer is 50 cm long). (b) Large-scale (amplitudes up to several hundred meters and half wavelengths about 50 m) F_{P1} folds on cliff faces on Værøy (cliff face is 125 m high). (c) Tops-west shears cutting D_{P1} mylonites in amphibolite on Værøy.

ment-cover shear zone. Conditions of mylonitic development of the tops-SW, D_{P2}, shears, based on microstructural observations, vary from similar to that inferred for the S_{P1} mylonitic foliation to a lesser degree of dynamic recrystallization than is observed in S_{P1} (e.g., brittle broken and displaced feldspar and quartz LPO is more prominent in S_{P2}). Although some of the D_{P2} shears may be antithetic D_{P1} shears, the differences in microstructural development coupled with the occurrence of the major tops-SW shear zone indicate to us that they largely formed after or during the latter stages of D_{P1} shearing, and hence justifies our tentative assignment to a separate D_{P2} event.

[20] Our interpretation that the D_{P2} shear zones reflect higher crustal level deformational conditions for formation is consistent with progressive extensional unroofing of the S_{P1} shear zones. Later formed, small-scale, brittle faults (<5 cm displacement) and zones of fracture cleavage assigned to D_{P3} are more common on northern Værøy and further indicate such progressive unroofing. The brittle D_{P3} structures may correspond to the same event that produced the D_5 brittle faults in western Ofoten and on Vestvågøy.

3.3. Røst

[21] The Røst district consists of hundreds of small islands that are separated by relatively shallow water with dangerous tidal currents (Figure 4b). Mapping by *Holloman* [1996] and *Waltman* [1997] documents a complex structural interleaving of basement and cover in Røst due to recumbent folding and shear zone development. These structures have been gently warped around the nose of a late stage, SW plunging fold (Figures 4 and 6) that roughly corre-

sponds to the crest of the Lofoten culmination (i.e., "ridge" of *Talwani and Eldholm* [1977]). The sequence of fabric and structural development in Røst appears to be very similar to that described for Værøy. The main foliation on Røst, particularly in the southern parts, is defined by an upper amphibolite facies metamorphic schistosity that is locally mylonitic; in other words, retrogressive mylonites are less common on Røst than on Værøy. Also, unlike Værøy and Vestvågøy, granitic basement lithologies of Røst are penetratively sheared at all exposed structural levels. Basement-cover contacts on Røst are marked by mylonites with fabrics (Figure 5g) and kinematic indicators (predominantly tops-northeast) that correspond with the tops-northeast D_{P1} event on Værøy. As on Værøy, local tops-west shears overprinted and reactivated structures and fabrics within the basement-cover shear zone. West vergent ductile flow folds on Røst are similar in appearance to F_{P1} folds described on Værøy, and similarly have folded the main S_{P1} mylonitic foliation, but were not observed to root into S_{P1}. In addition, unlike the F_{P1} folds on Værøy, these folds on Røst do not appear to have sheath-like geometries; rather, they plunge mainly to the northwest (Figure 6). Combined with the overall WSW plunge of elongation lineations associated with these structures (Figure 6), we interpret these folds on Røst to correspond to the tops-west D_{P2} event on Værøy. Minor, late, generally tops-west brittle faults and tight joint sets overprint D_{P1} and D_{P2} structures and fabrics and thus are interpreted as D_{P3} structures.

[22] The southwesternmost islands of Røst (Skomvær and the surrounding islands) are dominated by high-grade migmatites that notably contrast with the Leknes group in other parts of Røst and Lofoten in general. Peak metamorphic porphyroblasts in these gneisses are commonly undeformed (Figure 5h). Element-partitioning thermobarometry on the peak assemblage garnet-kyanite-orthoclase-plagioclase-biotite-muscovite-rutile-illmenite in samples from Skomvær document equilibrium pressure-temperature conditions of about 9.2 kbar and 760°C, which are consistent with petrogenetic grids and an inferred pressure-temperature pathway for the pelitic rocks [*Mooney*, 1997]. Major and trace element zoning in porphyroblasts from the migmatities corroborate high-pressure, upper amphibolite-facies conditions and a subsequent, prolonged high-temperature thermal history [*Waltman*, 1997].

4. Previous Geochronology From Ofoten-Troms and Lofoten-Vesterålen

[23] The regional timing of Caledonian metamorphism and cooling in the Troms-Ofoten region (Figure 2) has been addressed by numerous studies [*Hodges*, 1985; *Tilke*, 1986; *Tucker et al.*, 1990; *Anderson et al.*, 1992; *Dallmeyer and Andresen*, 1992; *Gromet and Andresen*, 1993; *Cumbest et al.*, 1994; *Coker et al.*, 1995; *Northrup*, 1997]. U/Pb zircon ages of pretectonic intrusions in the Narvik Nappe Complex [*Tucker et al.*, 1990; *Northrup*, 1997] are within the range of 437 ± 2 Ma and provide an older bound for the timing of Caledonian metamorphism in Ofoten. *Coker et al.* [1992] and *Northrup* [1997] estimated the timing of peak metamorphism in schists and migmatites of Ofoten at circa 432 ± 2 Ma on the basis of U/Pb zircon and/or monazite ages. Hornblende and muscovite $^{40}Ar/^{39}Ar$ mineral ages in Troms and Ofoten support a protracted Silurian-Devonian cooling history of middle crustal rocks [*Coker et al.*, 1995; *Northrup*, 1997] that differs from the style of rapid and profound, Early Devonian tectonic unroofing evident in southwestern Norway [e.g., *Andersen and Jamtveit*, 1990]. However, an episode of extensional unroofing and detachment faulting at circa 395 Ma is indicated by dating of synkinematic metamorphic minerals in Troms-Ofoten [*Gromet and Andresen*, 1993; *Cumbest et al.*, 1994], which overlaps with extension in southwestern Norway [*Andersen*, 1993; *Andersen and Jamtveit*, 1990; *Andersen et al.*, 1991].

[24] *Hames and Andresen* [1996] reported laser $^{40}Ar/^{39}Ar$ muscovite ages that confirmed Silurian, Caledonian metamorphism and a protracted cooling history for rocks exposed in Lofoten. Intracrystalline $^{40}Ar/^{39}Ar$ ages for a single muscovite porphyroblast from Leknes group schist on Vestvågøy have a core rim range of circa 425-365 Ma. This intracrystalline range is similar to the overall age range reported by *Coker et al.* [1995] and *Northrup* [1997] for the regional Ofoten-Troms cooling history, as determined by multiple U/Pb and $^{40}Ar/^{39}Ar$ thermochronometers. For muscovite in the kyanite-orthoclase grade gneisses of Røst, southwestern Lofoten, *Hames and Andresen* [1996] reported core rim $^{40}Ar/^{39}Ar$ ages of circa 315–270 Ma. The Carboniferous-Permian intracrystalline ages reported from high-grade gneisses on Røst are markedly younger (∼100 m.y.) than comparable ages obtained in Vestvågøy and farther east in Ofoten and Troms. These results were interpreted to indicate a protracted, episodic Devonian-Permian unroofing history for the high-grade metamorphic rocks in Lofoten. Additional $^{40}Ar/^{39}Ar$ data in combination with new structural data of this study allow us to further define the tectonic context of the Silurian-Permian metamorphic and thermal history.

5. New $^{40}Ar/^{39}Ar$ Data for Lofoten-Vesterålen

[25] Figure 8 presents the results of single-crystal total fusion analyses for fabric-forming muscovite for seventeen samples from Lofoten-Vesterålen and two samples from the adjacent island Senja (Figure 1). From each sample, approximately fifty muscovite crystals were picked by hand under a binocular microscope for irradiation. These crystals were nominally 1 mm in diameter and were chosen as ones representative of a given fabric. Following initial selection and irradiation, about ten crystals were selected from each sample aliquot for individual analysis by laser fusion following standard procedures described previously [e.g., *Hodges et al.*, 1994]. Full $^{40}Ar/^{39}Ar$ data tables and sample locality information are presented in the auxiliary material[1]. As the radiogenic yields for all analyses are consistently high (typically greater than 98%), and the ages for a given sample are relatively consistent, the $^{40}Ar^*/^{39}Ar_K$ ratios for

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/tc/2003TC001522.

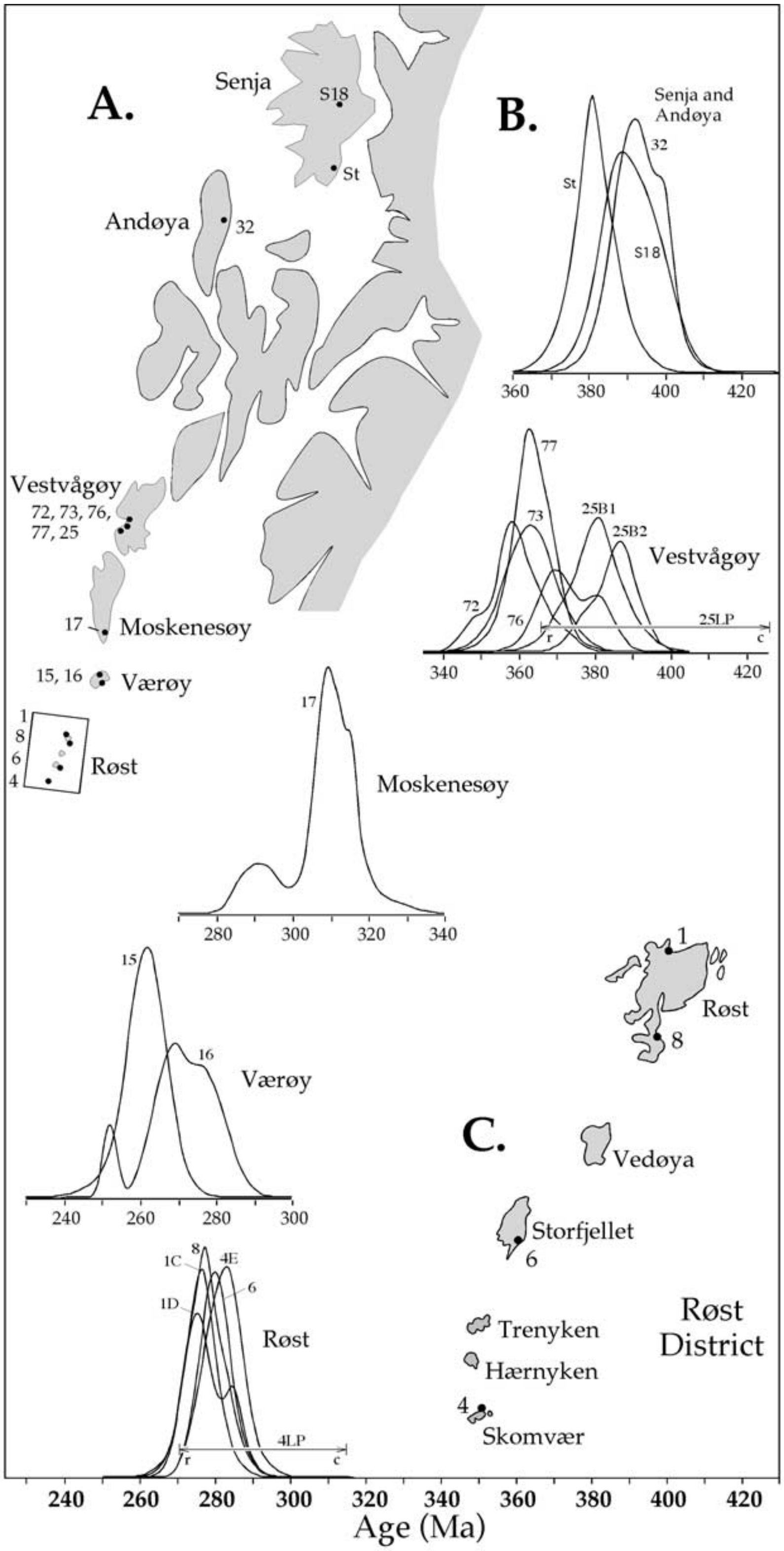

Figure 8. Results of single-crystal total fusion analyses for fabric-forming muscovite from 17 samples in Lofoten-Vesterålen. The *y* axis of the plot equates to geographic position with northeast at the top and southwest at the bottom; the *x* axis is age.

each sample are also very consistent and do not vary in correlation with any "excess" argon component. Thus we choose to report the statistical ages for each sample of this study as the mean and standard error of the mean for all single-crystal analyses of that sample, at the 95% confidence level, and to represent the range of ages for each sample with the cumulative probability plots of Figure 8. Cumulative probability plots are commonly used to represent the distribution of single-crystal analyses for a given sample [cf. *Copeland and Harrison*, 1990; *Northrup*, 1997; *Adams and Kelley*, 1998; *Sherlock*, 2001]; such probability plots are constructed by assuming that the age and standard deviation for each analysis represent the mean and standard deviation of a normal probability distribution, and then the apparent age distributions for the ten or so analyses from each sample are summed to generate the cumulative probabilities as depicted in Figure 8.

[26] Undeformed muscovite porphyroblasts that have overgrown foliation in basement metagranite on Andøya yield a relatively simple, Gaussian age distribution with a mean of 393 ± 3 Ma (Figure 8). This sample from Andøya was collected directly beneath the stratigraphic contact with Jurassic sandstones reported by *Sturt et al.* [1979]. The results for two additional samples collected on the island Senja are broadly similar: Sample 18 was collected in mylonitic granite 5 m beneath the basement allochthonous cover contact on Senja, where there is considerable recovery and postdeformational growth of all silicates including muscovite [*Cumbest*, 1987; *Hames*, 1988; *McKinney*, 1989] (similar to the textures of Figures 5a and 5b). Muscovite porphyroblasts from sample 18 yield a mean age of 391 ± 2 Ma. A somewhat younger age of 381 ± 2 Ma was determined for deformed and recrystallized muscovite from a shear zone near Stonglandsiedet, Senja, where basement of the Western Gneiss Region is imbricated with allochthonous Caledonian cover [*Clark*, 1989]. The mean ages of 381–393 Ma presented in this study for the Western Gneiss Region of Andøya and Senja are typical of the Early Devonian muscovite ages of allochthonous Caledonian rocks exposed on the mainland of Ofoten and southwestern Troms [e.g., *Coker et al.*, 1995; *Northrup*, 1997].

[27] Muscovite was prepared for six samples from the Leknes group schists on Vestvågøy. Two size fractions of muscovite porphyroclasts, samples 25B1 and 25B2, were separated from mylonitic kyanite-bearing gneiss of the Leknes group, near the basal contact with granitic gneiss of the WGR. These porphyroclasts yield ages of circa 380–385 Ma (Figure 8), notably older than samples of finer-grained muscovite from the Leknes group schists. Samples 73a, 72a, 76, and 77 are all relatively fine-grained schists of the Leknes group, and their fabric-forming muscovite porphyroblasts yield mean ages of circa 360–370 Ma. The total range of *intercrystalline* age variation for different samples of the Leknes group on Vestvågøy reported in this study is comparable to the younger intracrystalline ages reported earlier by *Hames and Andresen* [1996]. In the earlier study, *Hames and Andresen* [1996] obtained spot fusion ages from a single, undeformed, large muscovite porphyroblast sampled from a boudin of kyanite-bearing gneiss surrounded by a D_4 mylonitic fabric (same locality as the sample 25 discussed above); these intracrystalline ages ranged from circa 420 Ma near the core of the crystal to circa 365 Ma near the rim (indicated by the line labeled "25LP" in Figure 8), a result that *Hames and Andresen* [1996] interpreted to reflect differential argon retention during cooling within a single, relatively undeformed crystal. The results obtained for smaller, fabric-forming micas from Vestvågøy that are strongly affected by late stage deformation sensibly yield a complex age distribution that arises from variations in the size, defect density, and growth history of individual crystals.

[28] Muscovite is sparingly present in pegmatites that intrude basement gneisses in the village of Å at the southern tip of Moskenesøy (Figure 1). These pegmatites are undeformed, and were interpreted by *Griffen et al.* [1978] to be Caledonian; previously reported K/Ar data indicate an age of 317 Ma for a bulk sample of muscovite from these pegmatites [*Griffen et al.*, 1978]. We resampled muscovite from these pegmatites, and obtained laser fusion ages for 14 crystals, with a mean age of 308 ± 5 Ma (Figure 8) and a similar mode. These muscovite crystals are undeformed, and their age is interpreted to represent the timing of cooling through the crystal's argon retention temperatures (~350–400°C).

[29] Two muscovite samples from Værøy were selected for $^{40}Ar/^{39}Ar$ analysis. Sample 16 is of muscovite-biotite gneiss from the allochthonous schists on Værøy. Muscovite crystals in sample 16 are typically deformed, asymmetric porphyroclasts that indicate a tops-northeast sense of displacement; foliation in this sample is defined by preferred alignment of these porphyroclasts, recrystallized muscovite, and chlorite porphyroblasts. Ten muscovite crystals from sample 16 have a relatively broad and bimodal age distribution, with a mean age of 271 ± 5 Ma and a mode of 269 Ma. Sample 15, in contrast, was collected from the granitic basement of Værøy and it contains hydrothermal muscovite formed in a D_{P3} brittle fracture. Muscovite occurs in sample 15 within and parallel to the D_{P3} fractures as an undeformed, "apple green" celadonitic mica with a radiating habit indicating hydrothermal growth. Laser fusion analyses for ten crystals of this celadonitic muscovite yield a Gaussian age distribution with a mean of 261 ± 2 Ma (Figure 8). This mean age for sample 15 is interpreted to record the timing of muscovite growth in the D_{P3} fracture.

[30] Five samples were selected from the Leknes group metamorphic rocks of the Røst district for laser $^{40}Ar/^{39}Ar$ analysis of muscovite (Figure 8). In general, results for the samples from Røst are much less variable than for any of the other samples in this study (which is also consistent with the observation that peak metamorphic mineral assemblages in the Leknes Group rocks of Røst appear thoroughly recrystallized and often less deformed than on Værøy or Vestvågøy). Samples 1C and 1D, from S_{P1} mylonites developed along contacts between the Leknes group and granitic basement on the northern end of Røst contains synkinematic and deformed muscovite (see

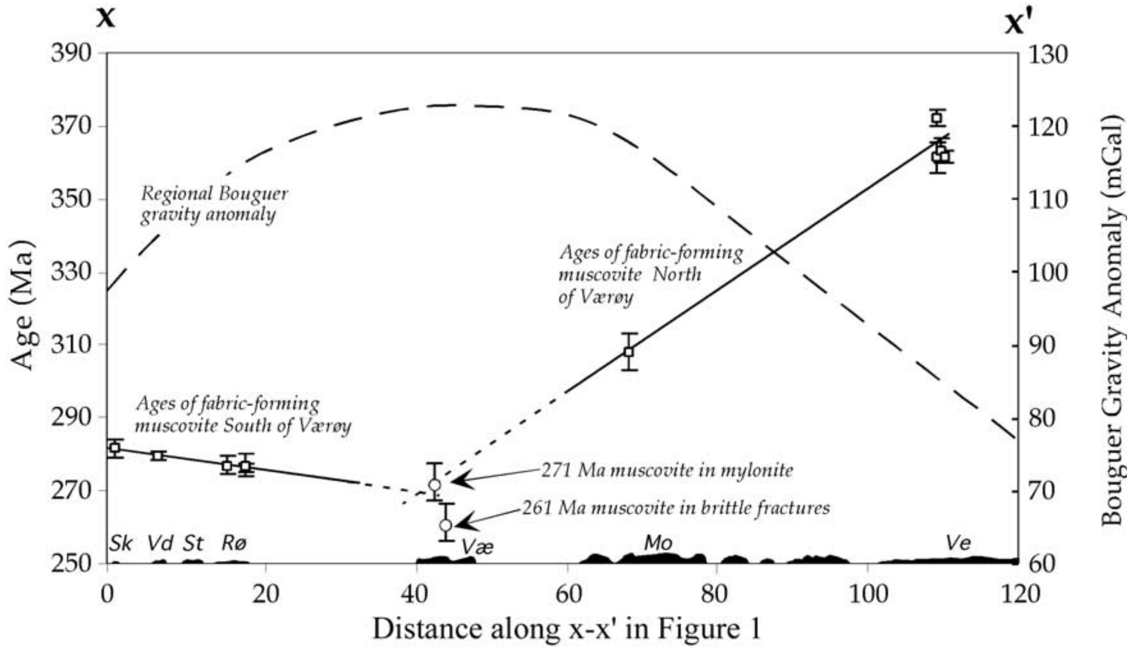

Figure 9. Mean age of samples collected throughout Lofoten plotted against distance.

Figure 5g) with mean ages of 276 ± 1 and 277 ± 3 Ma, respectively. Deformed, synkinematic muscovite in samples 8 and 6, from the islands of Vedøya and Treneken occurs in similar S_{P1} foliations and defines ages of 277 ± 2 and 280 ± 1 Ma. Sample 4 is from undeformed kyanite-orthoclase grade gneiss (see Figure 5h) on the southernmost island, Skomvær. Single-crystal fusion analysis of 10 fabric-forming, relatively small (~1–2 mm diameter) muscovite porphyroblasts from sample 4 yield a mean age of 282 ± 2 Ma. A large muscovite porphyroblast taken from these same gneisses (sample 4 of *Hames and Andresen* [1996]) yielded an intracrystalline core rim age range of circa 318–268 Ma (line "4LP" in Figure 8). The intercrystalline and intracrystalline age variations in muscovite from sample 4 are interpreted to reflect argon retention during cooling, whereas ages from other samples from Røst (1, 6, and 8) are likely controlled by some combination of cooling history and superimposed deformation and recrystallization.

[31] Inspection of Figure 8 indicates that there is a regular pattern to the distribution of muscovite ages in Lofoten. From the maximum single-crystal ages of circa 393 Ma determined for muscovite bearing metagranite on Andøya, similar to ^{40}Ar/^{39}Ar cooling ages determined on Senja (Figure 8) and the Caledonian mainland [*Coker et al.*, 1995], ages tend to become younger southwestward in Lofoten, with typical modes for fabric-forming muscovite on Vestvågøy of about 365 Ma, and about 310 Ma for Moskenesøy. The minimum ages determined from metamorphic muscovite, in schists or recrystallized in mylonitic shear zones, occur for sample 15 of Værøy, and the mylonitic fabrics are postdated by development of hydrothermal muscovite in fractures dated at circa 261 Ma. Southwest of Værøy, however, the mean muscovite ages on Røst become noticably older, ranging from 276 to 282 Ma.

6. Interpretations of Muscovite Age Relationships in Lofoten-Vesterålen

[32] The regional age variation suggested in Lofoten by Figure 8 is actually very regular and systematic, as illustrated in Figure 9. The mean age and associated uncertainty for each sample is plotted against distance in Figure 9, making it clear that a reversal in the regional trend of muscovite ages occurs in the vicinity of Værøy. Two lines were fit to the data north and south of Værøy by simple regression (data for sample 15 and 16 from Værøy were not included in either fit), and these intersect within the immediate vicinity of Værøy at a "minimum" of circa 270 Ma. The fact that a minimum age in the vicinity of Værøy as suggested by regular, regional age variation is essentially the same as the age of 271 ± 5 Ma documented for sample 16 from Værøy suggests a systematic relationship to the muscovite ages throughout Lofoten-Vesterålen. Such a systematic relationship is further suggested by coincidence of a regional, positive gravity anomaly with the muscovite ages; higher Bouguer gravity anomaly (and thinner crust as previously discussed) appears correlated with younger ages, and the youngest ages and highest gravity anomaly occur in approximately the same location (Figures 1 and 9). We suggest that the processes that resulted in argon isotopic closure of muscovite in Lofoten-Vesterålen (a combination of cooling, deformation, and crystal growth history) are also responsible for late Paleozoic stages of development of the regional gravity signature in Lofoten. This process is

inferred to be the Paleozoic crustal extension and attenuation that resulted from the gravitational instability of thickened, Caledonian orogenic crust, analogous to the classic development of a metamorphic core complex.

[33] We have taken care to note that muscovite in the samples of this study exhibits a range of textural relationships with respect to deformational features. In cases where the fabric-forming muscovite is relatively undeformed (e.g., sample 4, 15, or 32) the resulting age range is Gaussian and considered to reflect cooling and argon retention in a restricted size range of crystals. In other cases for deformed muscovite (e.g., sample 16) the age range likely reflects a combination of cooling history, argon loss via deformation mechanisms [e.g., *Dunlap and Kronenberg*, 2001], muscovite growth and recrystallization through multiple stages of deformation [e.g., *Dunlap*, 1997; *Di Vincenzo et al.*, 2001], and retention of radiogenic argon produced in the muscovite prior to deformation [e.g., *Hames and Cheney*, 1997].

[34] The deformational textures of sample 16 and surrounding mylonitic rocks of D_4 shear zones on Værøy (Figures 5e and 5f) are comparable to the cases where the age of low-grade mylonitic deformation was approximated by the age of deformed and recrystallized muscovite [*West and Lux*, 1993; *Dunlap*, 1997]. We further suggest that the fine mylonitic recrystallization and strain features evident in the D_4 shear zone of Værøy would not be present if metamorphic temperatures had remained relatively high (>300°C or so) for a substantial length of time following deformation. Thus the age of 271 ± 5 Ma is interpreted to indicate a maximum estimate for the timing of D_4 deformation, as it is not likely to represent a metamorphic cooling age, and yet some inheritance of accumulated ^{40}Ar may persist and cause the muscovite ages to overestimate the timing of deformation. We interpret the timing of D_4 mylonitic deformation to be effectively bracketed between the age of 271 ± 5 Ma for deformed muscovite from Værøy (sample 16) and 261 ± 2 determined for the hydrothermal muscovite in brittle fractures on Værøy (sample 15).

7. Discussion of Tectonic Evolution

7.1. Caledonian Contraction

[35] The thermochronological results from Vestvågøy, in consideration with results presented by *Hames and Andresen* [1996] and *Northrup* [1997], indicate that the timing of metamorphism and thrusting coincided with the main Scandian (Silurian, circa 425 Ma) phase of the Caledonian orogeny that is well documented in western Ofoten (Figure 9). The structural and metamorphic expressions of D_1–D_4 on Vestvågøy are very similar to the D_1–D_4 Caledonian events documented in western Ofoten (compare Table 1). In both areas, early stage, Silurian, tops-east, synmetamorphic D_2 thrusts imbricated the basement and cover and emplaced Caledonian allochthons. The disappearance of D_2 fabrics structurally downward into the basement on Vestvågøy [*Tull*, 1978; *Klein et al.*, 1999] closely mimics the style of deformation that has been long recognized along the basement-cover contact in western Ofoten [*Bartley*, 1982a; *Tull et al.*, 1985]. Minimum thermobarometric estimates of the D_2 metamorphic peak recorded by metapelitic rocks from Vestvågøy range from 7.6 to 9.2 kbar and 560 to 660°C and overlap the higher-grade range of conditions reported by *Royden and Hodges* [1984] and *Steltenpohl and Bartley* [1988]. Metamorphic facies development and average, inferred P-T conditions in Ofoten and Vestvågøy are lower, however, than the minimum estimates of 9.2 kbar and 760°C for kyanite + orthoclase + muscovite gneiss found in southwestern Lofoten on the islands of Røst. Thus conditions of metamorphism recorded by the Vestvågøy and Røst metapelites are consistent with Lofoten having been the more deeply subducted part of the Baltic margin in comparison with western Ofoten. The ^{40}Ar/^{39}Ar mineral cooling trends reported by *Coker et al.* [1995] for Ofoten clearly continue into Lofoten, consistent with synchroneity of the D_2 thermal event in both areas. Later stage, post-D_2 structures between the two areas also have similar geometries, kinematics, fabrics, and relative timing relationships, which also is consistent with the mineral cooling data. Our results, therefore, support the contention that the WGR in Lofoten is continuous with the Baltic basement of the foreland. The lack of Caledonian effects in large tracts of the Lofoten WGR must reflect a lack of fluids in the dry, granulite-facies Baltic crust [*Bartley*, 1982a; *Hodges et al.*, 1982; *Olesen et al.*, 1997].

7.2. Late Caledonian (Devonian-Carboniferous) Extension

[36] Prior to this study, little has been reported from Lofoten concerning Devonian extension. This is due mainly to the fact that there are no Devonian sedimentary rocks exposed anywhere in north Norway, in contrast to the field relationships of southwestern Norway. Nonetheless, on the adjacent mainland in Ofoten workers have been evaluating what, if any, structures there might be related to Devonian extension. *Steltenpohl and Bartley* [1988] first gave detailed descriptions and geometric and kinematic observations on a set of major, late Caledonian, northeast-southwest trending backfolds with tops-west vergence. The early Devonian timing that these authors inferred for this event is consistent with Devonian extensional collapse. *Rykkelid* [1992] and *Rykkelid and Andresen* [1994] further investigated the tops-west backfolds and also recognized weakly developed tops-west ductile shears that had reactivated parts of the basal Caledonian decollement in Ofoten. The same authors argued that these structures formed due to extensional collapse. Westward younging ^{40}Ar/^{39}Ar mineral cooling trends recognized by *Coker et al.* [1995] led them to hypothesize that a Devonian detachment lay west of Ofoten, perhaps in Lofoten or farther west, offshore. Later, *Northrup* [1996] interpreted foliation boudinage along parts of the basal Caledonian thrust in Ofoten to reflect noncoaxial flow in the midcrust. *Northrup's* [1996, 1997] studies indicate that evidence for major Devonian extension is lacking in Ofoten, although his observations were compatible with a model of Devonian extension to the west of Ofoten.

[37] We interpret relationships exposed on Vestvågøy to reflect the transition from generic, tops-east Caledonian thrusting to Devonian tops-west extension. On Vestvågøy,

the predominant synmetamorphic D_2 Caledonian thrusting plan was directed east-southeast (Figure 4), identical to that observed in the more forelandward setting of Ofoten. Caledonian thrusts on Vestvågøy were reactivated by late, high-level, tops-west D_4 shears, comparable to the Devonian deformation plan recognized in western Norway [*Andersen et al.*, 1991; *Torsvik et al.*, 1992]. Our ^{40}Ar/^{39}Ar isotopic data indicate that cooling associated with D_4 shearing through muscovite closure temperatures occurred by circa 365 Ma. *Hames and Andresen* [1996] suggested that this timing is consistent with the deposition of Devonian-Carboniferous clastic strata preserved offshore in half grabens flanking the Lofoten Ridge and other associated basement culminations. The pervasiveness of post-Caledonian, Permian mylonitization in rocks of Værøy and Røst, which apparently obliterated evidence of the Caledonian D_4 event, precluded us from making inferences on the nature of the Devonian-Carboniferous extensional event on these islands. Regardless, the tops-west D_4 event in Lofoten correlates well with the tops-west D_4 back folding event in Ofoten [*Klein et al.*, 1999], and thus we attribute these structures to record gravitational collapse of crust thickened during Caledonian orogeny.

[38] The D_4 extensional event in Lofoten is distinct from the Devonian extensional event in western Norway in several regards. First, the timing that we have determined for D_4 is substantially younger than that recorded in rocks of western Norway. If these are related events, then D_4 in Lofoten was delayed some 15 to 20 m.y. relative to extension in west Norway. Second, the lack of Devonian cooling ages from rocks of Værøy and Røst requires that the presently exposed levels experienced elevated temperatures well into the Permian. In other words, while tremendous magnitudes of Devonian exhumation occurred in western Norway, the crust exposed in southwest Lofoten remained deeply buried for another 100 m.y. before it was substantially exhumed. Thus we see no evidence in exposed rocks of southwest Lofoten that requires a tremendous Devonian extensional event as is preserved in west Norway. This does not preclude, however, that evidence for such an event is concealed offshore to the west of Lofoten, or that evidence for it in southwest Lofoten was obliterated during the pervasive Permian event.

7.3. Latest Caledonian (Late Devonian-Carboniferous) Left-Slip Shearing

[39] The Devonian-Carboniferous, tops-west structures on Vestvågøy contain a persistent oblique component of left-slip movement (Figure 10). *Van Winkle et al.* [1996] report precisely the same type of oblique, tops-west, left-slip displacement on shear zones that are concentrated along the basement-cover contact in western Ofoten. *Steltenpohl and Bartley* [1988] reached the same conclusion based on their analysis of northeast-southwest trending D_3 crossfolds in western Ofoten-Tysfjord, which require orogen-parallel, lateral movements. Left-slip movements that rotated earlier formed structures also resulted in the prominent northwest-southeast structural grain of rocks on Hinnøy. Therefore we suggest that there may have been significant lateral movement associated with Devonian extension in north Norway, although the magnitude is yet to be determined. It is possible that these left-slip shear zones formed in a fashion similar to those that flank the southeast sides of the scoop-shaped Devonian basins in southwestern Norway; however, as noted above, the Devonian event in our area is somewhat younger. Alternatively, left slip in northern Norway may be linked to the pervasive Devonian-Carboniferous strike-slip zones well known in the United Kingdom, the northern Appalachians, and parts of western Norway [*Harland and Gayer*, 1972; *Van der Voo and Scotese*, 1981; *Flinn*, 1985; *Currie and Piasecki*, 1989; *Grønlie and Roberts*, 1989; *Robinson*, 1991; *Hutton and McErlean*, 1991].

7.4. Permian Extension

[40] Our recognition of midcrustal level, Permian extensional structures and penetrative fabrics pervading exposures in southwest Lofoten, on Værøy and Røst, is a remarkable find that appears unique in the in the exposed Caledonides. Although Permian grabens and associated sediments are well documented in offshore areas, prior to our findings, the only exposed Permian extensional structures known in Norway were those that had reactivated the Dalsfjord fault in western Norway [*Torsvik et al.*, 1992], those that formed the Oslo rift [*Neuman et al.*, 1992], and a group of basaltic dikes and associated faults recognized along the west coast of southern Norway [*Førseth et al.*, 1976; *Torsvik et al.*, 1997]. More recently, *Dunlap and Fossen* [1998] report ^{40}Ar/^{39}Ar data for K-feldspars from western Norway that also are indicative of cooling at $\sim$300–250 m.y., which they interpret to reflect extensional instability. The character of Permian extension in Lofoten therefore has important implications for Norwegian margin development.

[41] In contrast to the pervasive record of Permian deformation in rocks on Værøy and Røst, it appears that, at most, Permian extension in Vestvågøy and more eastern areas, including the mainland, was manifest only in young but undated, high-angle, brittle faults [*Forslund*, 1988; *Bartley*, 1982b; *Steltenpohl*, 1987; *Van Winkle et al.*, 1996; *Olesen et al.*, 1997; *Klein and Steltenpohl*, 1999]. Our ^{40}Ar/^{39}Ar and structural studies in Lofoten document that the boundary between southwestern rocks that experienced penetrative Permian ductile deformation and those to the northeast that did not rests between exposures in southern Moskenesøy and northern Værøy. Although the boundary has not been observed, seven key observations made during our field and isotopic studies allow inferences to be made on the nature and position of this boundary. (1) The pervasive, D_2, Caledonian metamorphic fabric in rocks on Vestvågøy and the mainland in Ofoten range from having been strongly overprinted to completely obliterated by the retrogressive, D_{P1} fabrics on Værøy and Røst. (2) Structural formlines of the D_{P1} foliation on Værøy and Røst have the overall structural configuration of a domal culmination, which we refer to as the Værøy/Røst culmination. (3) Regional patterns of ^{40}Ar/^{39}Ar muscovite data of this study young to circa 269 Ma on Værøy, suggesting a core of basement that experienced unroofing in the Late

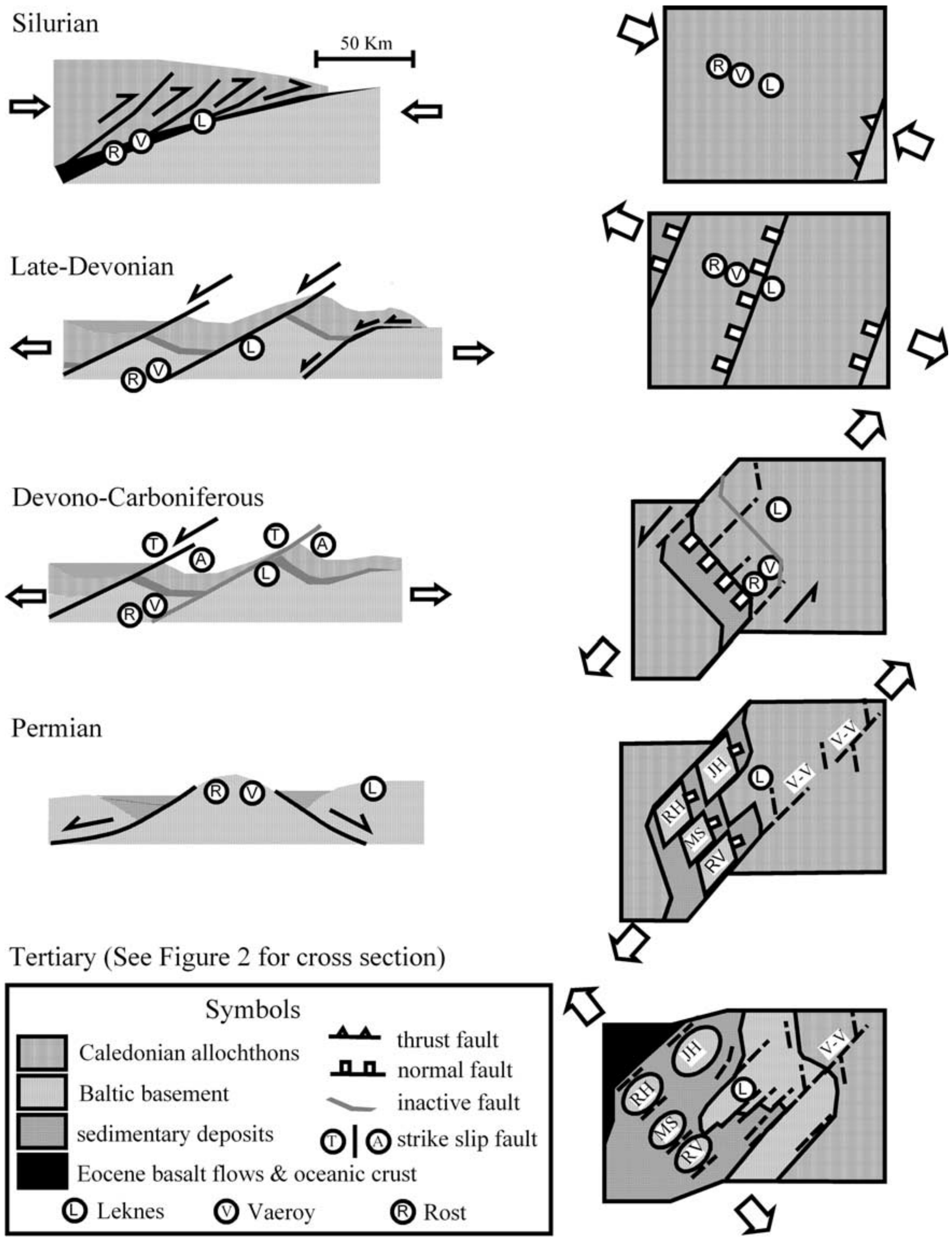

Figure 10. Cartoon diagram depicting the sequential development of the Norwegian margin in the Lofoten region (see section 7 for details). Large arrows illustrate horizontal principal stress directions controlling the kinematic plan for each event. Transect lines for the cross sections roughly parallel the direction of the principal stress arrows. Note that the scale of cross sections and map areas is smaller for the Devonian-Carboniferous diagrams to better illustrate details in the Lofoten area. Note that increased area of exposed basement through time reflects achievement of deeper erosional levels. JH, Jenegga high; MS, Marmele Spur; RH, Røst high; RV, Røst and Værøy; V-V, Vestfjorden-Vanna fault zone.

Permian. (4) The domal basement core suggested by $^{40}Ar/^{39}Ar$ ages corresponds to the "Lofoten ridge" and to the anomalous gravity and magnetic highs [*Mjelde et al.*, 1993]. (5) The trend of kinematic displacement determined for the D_{P1} event is tops-northeast, parallel to the Lofoten ridge. (6) Later Permian, transitional plastic-brittle and brittle normal faults further extended the Lofoten ridge in a northeast-southwest direction. (7) Northeast-southwest trending, high-angle, horst-and-graben bounding faults that flank the Lofoten and other associated ridges clearly truncate the Permian structures and metamorphic edifice.

[42] The Permian detachment must lie between the northern end of Værøy and southern Moskenesøy, and thus must have a roughly east-west trend in that area. The detachment lies above Værøy and Røst and the attitudes of the Permian mylonites indicate that it has a low-angle dip; dips are shallow to moderate and fan out toward the southwest on Røst, they progressively change from moderate southwest on southern Værøy to subhorizontal and then shallow northeast in outcrops along the most northern shore of Værøy (Figure 4). Projecting the shallow northeast dips northward toward Moskenes, the detachment must dip beneath Moskenes, which is consistent with Værøy and Røst being the footwall of the Permian metamorphic core. This geometry necessitates a substantial magnitude of vertical throw and tops-northeast heave along the Permian detachment.

[43] Our previous work [*Holloman*, 1996; *Klein*, 1997; *Mooney*, 1997; *Waltman*, 1997; *Klein et al.*, 1999; *Klein and Steltenpohl*, 1999] led us to suggest that the Caledonian metasedimentary units on each of these islands are correlative. Early, unpublished cross sections that we drew between Ofoten and Røst presumed that these units were simply connected along a single shear zone connecting with the basement-cover thrust in western Ofoten. We considered this shear zone to pass southwestward slightly above the present-day basement exposures in Lofoten and that high-angle normal faults had down-dropped the metasedimentary allochthons to expose the Leknes group. This parsimonious approach seemed justified considering that the Leknes group metasediments today all occur along the same erosional surface at the same elevation (i.e., sea level). Our structural and isotopic data indicate that the contact between the Leknes Group and basement on Vestvågøy represents the same level as the basement-cover contact in western Ofoten. This basement-cover contact simply appears to have been warped over the Lofoten basement north of Moskenesøya as well as the basement lithologies of Hinnøy (Figure 2).

[44] The basement-cover contact relations on Vestvågøy do not extend south to Værøy and Røst, however, for several reasons. First, our $^{40}Ar/^{39}Ar$ data indicate that deformation and cooling of mylonitic rocks in Værøy and Røst occurred approximately 150 m.y. after that for the basement-cover contact on Vestvågøy and in western Ofoten. Second, just prior to the Permian, the relatively lower-grade Leknes group metasediments on Vestvågøy that yield Devonian muscovite ages resided at a higher crustal level than did the Værøy and Røst basement-cover lithologies. This geometry combined with the tops-northeast kinematics of the Permian D_{P1} mylonites necessitates normal dip-slip motion along this detachment which had to have cut the previously formed shear zone connecting Vestvågøy with the basement-cover contact in western Ofoten (see Permian stage, Figure 10). Parallelism of the Permian mylonitic foliation with the basement-cover contact farther south on Værøy and Røst, however, indicates that this extensional shear zone merges with the ancient subduction zone boundary.

[45] Taken together, we interpret these findings to point to a western U.S. Cordilleran style of extension [*Coney*, 1980; *Armstrong*, 1982; *Wernicke*, 1985] for the tectonic evolution for southwest Lofoten. Earlier formed Caledonian thrusts clearly were reactivated during ductile Permian extensional shearing. Brittle on ductile overprinting of the Permian crystal-plastic shear zones records progressive unroofing of the extensional shears to shallower crustal levels. The anomalous, ~15 km mantle high that presently resides beneath the Lofoten (Figure 3) reflects uncompensated crust but its position very near to the Værøy/Røst Permian culmination is intriguing [*Løseth and Tveten*, 1996; *Olesen et al.*, 1997; *Olesen and Dehls*, 2001]. Although the modern geophysical signatures of this culmination have generally been considered to reflect Cretaceous to Tertiary extension, the isotopic and structural data of the present study suggests that evolution of this structure began by the Permian, and was strongly influenced by the regional Caledonian and Devonian-Carboniferous crustal setting.

[46] An exposed half graben containing mid-Jurassic rocks in contact with the basement on Andøya (Figure 2) reflects substantial post-Caledonian and pre-mid-Jurassic uplift, erosion, and deposition in the region of Vesterålen [*Dalland*, 1975; *Løseth and Tveten*, 1996]. Post-Devonian (?) to pre-Cretaceous age clastic sedimentary rocks also are inferred to reside in the upper plate along the flanks of the Lofoten ridge in the Skomvær subbasin and Vestfjorden basin. Vestfjord, a tongue of the Norwegian Sea, is a ~7 km deep half graben with a complex border fault against the Lofoten islands [*Brekke and Riis*, 1987; *Olesen et al.*, 1997]. The age of the sediments in the Vestfjord basin is uncertain. *Bøen et al.* [1984] suggested that Vestfjord was a Paleozoic basin. *Jørgensen and Navrestad* [1981] considered Vestfjord to be a region of major pre-Jurassic subsidence and sedimentation. *Mjelde et al.* [1996] inferred late Paleozoic to Early Mesozoic sediments in Vestfjord. Faults associated with Vestfjord project on to land into the Vestfjord-Vanna fault complex [*Forslund*, 1988]; paleomagnetic studies indicate these faults were active in the Permian [*Olesen et al.*, 1997]. Permian-Carboniferous extension also is documented in the Sørvær basin (Figure 2) at the northern terminus of the Vestfjord-Vanna fault complex [*Sigmond*, 1992]. The Skomvær subbasin is a ~5 km deep half graben flanking the Lofoten islands to the west along the steeply dipping Western Lofoten Border Fault [*Åm*, 1975; *Rønnevik and Navrestad*, 1977; *Løseth and Tveten*, 1996]. *Mjelde et al.* [1996] inferred post-Devonian (?) to pre-Cretaceous age clastic sedimentary rocks in the unexposed Skomvær subbasin. Also, *Olesen et al.* [1997] report that there is no evidence of Devonian sediments in the Skomvær subbasin

and describe geophysical constraints for inferred basal Cretaceous sequences in the basin.

[47] Rocks of southwest Lofoten, therefore, contain all the elements of a Cordilleran-style metamorphic core complex: plastically deformed metamorphic and plutonic basement in the footwall, a low-angle normal fault zone separating the hanging wall and footwall blocks, and synsedimentary cover rocks in the hanging wall.

7.5. Eocene Extensional and Continental Separation

[48] A rather simple, first-order reconstruction of the configuration of the pre-Eocene Norwegian margin in the Lofoten-Vestfjord region (see Permian and Tertiary stages, Figure 10) can be made using published maps of basement highs and corresponding deep basins [*Olesen et al.*, 1997]. There is a correspondence between the basement highs and lows indicating that the former were derived from the areas of the latter. There also is a straightforward kinematic plan for Eocene extensional movements in this region recorded by the first magnetic stripes formed within the nascent Norwegian Sea [see *Olesen et al.*, 1997]. Major basement highs (higher than −1 km below sea level) in this region include the Jenegga and Røst highs, the Marmele Spur, and, of course, the Lofoten archipelago (Figure 2). The following major basins are adjacent to these highs: the Ribban basin (with the Havbåen subbasin), the Skomvær subbasin, and the Vestfjord basin. These reconstructions are entirely consistent with our described field relations.

8. Implications for Interpretations of Regional Sedimentation Patterns

[49] The islands of Røst and Værøy are the expression of basement highs that continue southward from Lofoten to the submerged Nordland ridge (Figures 1, 2, and 3). These ridges form boundaries to the Vestfjord basin, a major center for subsidence and clastic sedimentation since the late Paleozoic [*Jørgensen and Navrestad*, 1981]. The region of the Nordland ridge is interpreted to actually have been a subsiding trough in the late Paleozoic, that underwent uplift, erosion and inversion in Permian-Triassic time [*Bøen et al.*, 1984; *Caselli*, 1987; *Blystad et al.*, 1995; *Sherlock*, 2001]. Single-crystal laser ages for detrital white micas recovered from ten Triassic to Cretaceous sandstones in the vicinity of the Nordland ridge range from 424 to 369 Ma [*Sherlock*, 2001], with an inverse relationship in which the Triassic sandstones generally contain the youngest micas and the Cretaceous sandstones contain the oldest micas. *Sherlock* [2001] interpreted the inverse relationship to record a history of erosion and deposition with two or more stages, from initial deposition of detritus from Caledonian metamorphic rocks in Silurian-Devonian basins that were subsequently uplifted and eroded with recycling and inversion of sediments into the Triassic-Cretaceous basin.

[50] The results of *Sherlock* [2001] are represented in Figure 11 for comparison with results of this study. The 424–369 Ma age range of detrital muscovite recovered from the Triassic-Cretaceous sandstones is similar to the single crystal age range of muscovite from metamorphic rocks and shear zones on Vestvågøy, Andøya, and Senja (Figures 1, 7, and 10), and we would suggest that the overall range is broadly similar to Caledonian mica ages determined in numerous studies of the Norwegian mainland [e.g., *Coker et al.*, 1995; *Northrup*, 1997]. In detail, the detrital muscovite age range most closely coincides with the ages we determined for Andøya and Senja, with few ages as young as those we determined for Vestvågøy, and some notably older detrital mica ages (between 400 and 424 Ma) for the Jurassic-Cretaceous sandstones. The fact that some ages for the detrital muscovite are significantly older than those found in metamorphic bedrock is to be expected for progressive erosion of the Caledonides from higher crustal levels that experienced earlier uplift and erosion to deeper levels as exposed today. Explanations for the tendency of older strata to contain younger micas are, however, equivocable.

[51] The multistage basin erosion and inversion model preferred by *Sherlock* [2001] is consistent with the stratigraphic and geochronologic data of their study, and with an inferred Permian-Triassic uplift event for the Nordland ridge. The Caledonides, however, generally are interpreted to have experienced tropical to subtropical conditions in the Jurassic-Cretaceous interval [e.g., *Sturt et al.*, 1979], which would presumably cause muscovite to be susceptible to clay-forming reactions. The preservation of detrital muscovite through multiple stages of erosion and deposition spanning millions of years thus might be unlikely. On the basis of our findings, it seems equally valid to suggest the following as an alternative to the inversion model of *Sherlock* [2001]. Initially, basins near the Nordland ridge were isolated in the Triassic and received detrital muscovite that was more locally derived and similar in age to that exposed in northern Lofoten (circa 360–380 Ma). Later, more distal sediment derived from rocks with ages comparable to the Caledonian mainland (circa 380–420 Ma) filled the basin through progressive linkage and eastward propagation of a Jurassic-Cretaceous drainage system.

[52] Perhaps most remarkable from comparison of single-crystal muscovite ages from the present study and *Sherlock* [2001] is the fact that no micas as young as 300–250 Ma were found among the eighty crystals analyzed from the Triassic-Cretaceous strata. This could indicate that the crustal levels and structures exposed today in southwestern Lofoten were buried and did not provide detritus through most of the Mesozoic. In other words, southwest Lofoten may have experienced uplift and erosion mainly through post-Cretaceous faulting. This suggested relationship could be tested by dating detrital micas from Late Cretaceous to Cenozoic strata in the vicinity of the Nordland ridge and Røst high.

9. Conclusions

[53] Although Caledonian metamorphic rocks in the Leknes area are 120 km removed from the comparatively well studied Caledonian rocks on the mainland in Ofoten, there is a straightforward correlation of the relative structural sequences identified between the two areas (Table 1). Timing of these Caledonian events also correlates

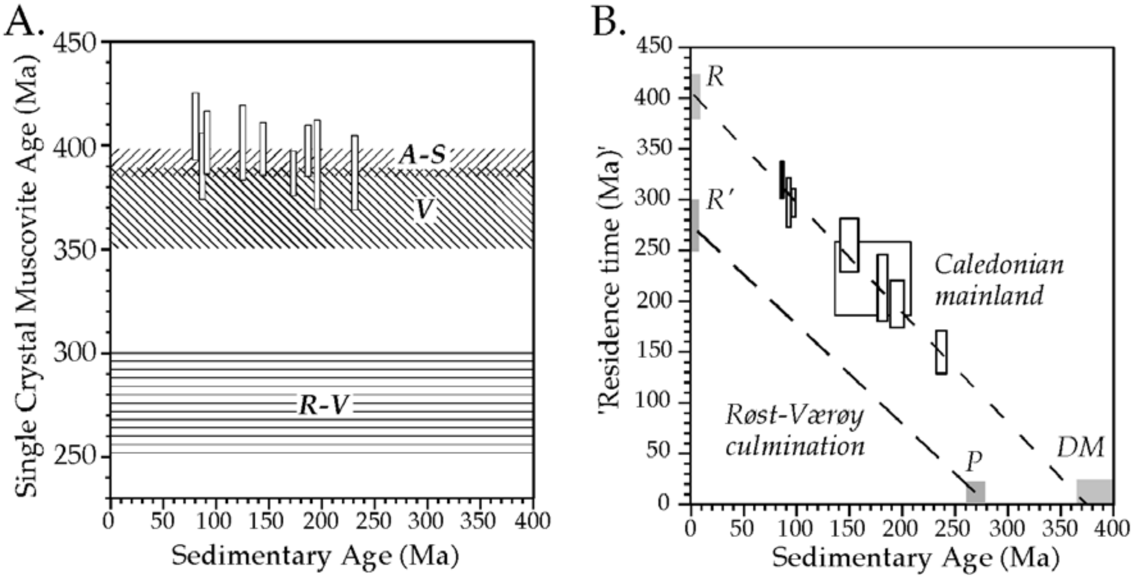

Figure 11. (a) Ranges of detrital muscovite ages and host strata from the study of *Sherlock* [2001] (data represented by the open, vertical boxes). These are generally comparable with the ranges of single-crystal ages determined in this study for metamorphic basement and allochthonous Caledonian rocks of Anjøya and Senja (diagonal pattern labeled "A-S"), and Vestvægøy, northern Lofoten ("V"). However, all of these mineral ages are dramatically older than comparable minerals exposed in the southwestern Lofoten islands of Røst and Værøy ("R-V"). (b) Detrital muscovite ages of *Sherlock* [2001] (shown as boxes). These record "residence times" that are similar to a hypothetical trend line defined by the presumed ages of Caledonian muscovite in Devonain molasse (DM) and recent sediments (R) derived from the present Caledonian mainland, and thus may be interpreted to reflect simple progressive erosion of Caledonian basement as exposed in the Norwegian mainland. However, if muscovite crystals with ages as presently exposed on Røst and Væroy were deposited in strata ranging in age from Permian (P) to recent (R′), the ages would presumably define a distinct trend as labeled P-R′.

well with those in Ofoten, clearly establishing that rocks in both areas experienced a similar tectonic history. During Caledonian contraction, rocks in Leknes are interpreted to have occupied a more western, more deeply subducted part of the Baltic margin (Silurian stage, Figure 10). The WGR in Lofoten, therefore, is continuous with the Baltic basement of the foreland. The lack of Caledonian effects in the basement rocks throughout large parts of Lofoten must reflect a lack of fluids in the preexisting igneous and granulite-facies metamorphic Baltic crust [*Bartley*, 1982a].

[54] Caledonian thrusts on Vestvågøy were reactivated during late Caledonian, tops-west, D_4 extension, much like faults associated with the Devonian basins of western Norway [*Seranne and Seguret*, 1987; *Andersen et al.*, 1991; *Osmundsen and Andersen*, 1994]. Tops-west, late Caledonian extension in Lofoten (Late Devonian stage, Figure 10) is consistent with comparatively minor extension reported in Ofoten by *Rykkelid and Andresen* [1994] and supports the hypothesis proposed by *Coker et al.* [1995], based mainly on ^{40}Ar/^{39}Ar dating in Ofoten, that a detachment lies west of the Lofoten islands. A southwest plunging component of normal and left-slip movement may reflect transtension associated with Late Devonian extension in the study area. Following Devonian-Carboniferous extension, the southwestern parts of the Lofoten ridge were tectonically unroofed by a Permian detachment fault that resulted in a domal, metamorphic core complex (Figure 9). The pervasiveness of the Permian event obliterated much of the earlier Caledonian fabrics and structures in southwest Lofoten. On Vestvågøy, however, Permian movements were manifest in an upper crustal level, brittle fault zone that cut the Leknes synform, allowing for preservation of Leknes group cover units in a down-dropped, half graben. Brittle on ductile overprinting of the Permian crystal-plastic shear zones records progressive unroofing of the extensional shears to shallower crustal levels. Following Permian northeast-southwest extension, the kinematic plan was wholly shifted to near due east-west extension, followed by Tertiary continental separation and initial formation of oceanic crust in the nascent Norwegian-Greenland Sea [*Eldholm*, 1986].

[55] The first, Eocene seafloor magnetic anomaly for the North Atlantic region occurs only about 60 km west of Lofoten-Vesterålen (see Figure 2), indicating profound Cretaceous to early Cenozoic extension in the region. However, consideration of the position of the present-day erosional surface and our interpretation of structures (Tertiary stage, Figure 10) and geochronologic constraints suggests that much of the regional structure present beneath the north central Norwegian shelf developed prior to circa 260 Ma.

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References

Adams, C. J., and S. P. Kelley (1998), Provenance of Permian-Triassic and Ordovician metagraywacke terranes in New Zealand: Evidence from ^{40}Ar/^{39}Ar dating of detrital micas, *Geol. Soc. Am. Bull.*, *110*, 422–432.

Åm, K. (1975), Aeromagnetic basement complex mapping north of latitude 62°N, Norway, *Bull. Nor. Geol. Unders.*, *316*, 351–374.

Andersen, T. B. (1993), The role of extensional tectonics in the Caledonides of south Norway: Discussion, *J. Struct. Geol.*, *15,* 1379–1380.

Andersen, T. B., and B. Jamtveit (1990), Uplift of deep crust during orogenic extensional collapse: A model based on field studies in the Sogn-Sunnfjord region of western Norway, *Tectonics*, *9*, 1097–1112.

Andersen, T. B., B. Jamtveit, J. F. Dewey, and E. Swensson (1991), Subduction and eduction of continental crust: Major mechanisms during continent-continent collision and orogenic extensional collapse, a model based on the south Norwegian Caledonides, *Terra Nova*, *3*, 303–310.

Anderson, M. W., A. J. Barker, D. G. Bennett, and R. D. Dallmeyer (1992), A tectonic model for Scandian terrane accretion in the northern Scandinavian Caledonides, *J. Geol. Soc. London*, *149*, 1–15.

Armstrong, R. (1982), Cordilleran metamorphic core complexes - From Arizona to southern Canada, *Annu. Rev. Earth Planet. Sci.*, *10*, 129–154.

Bartley, J. M. (1982a), Limited basement involvement in Caledonian deformation, Hinnøy, North Norway, and tectonic implications, *Tectonophysics*, *83*, 185–203.

Bartley, J. M. (1982b), Mesozoic high-angle faults, east Hinnøy, north Norway, *Nor. Geol. Tidsskr.*, *61*, 291–296.

Bartley, J. M. (1984), Caledonian structural geology and tectonics of east Hinnøy, north Norway, *Nor. Geol. Tidsskr.*, *396*, 1–24.

Blystad, P., H. Brekke, R. B. Færseth, B. T. Larsen, J. Skogseid, and B. Tørudbakken (1995), Structural elements of the Norwegian Continental Shelf II: The Norwegian Sea Region, *NPD Bull. 8*, Norw. Pet. Dir., Stavanger.

Bøen, F., D. Eggen, and J. Vollset (1984), Structures and basins of the margin from 62 to 69°N, in *Petroleum Geology of the North European Margin*, edited by A. M. Spencer et al., pp. 253–270, Graham and Trotman, Norwell, Mass.

Brekke, H., and F. Riis (1987), Tectonics and basin evolution of the Norwegian shelf between 62° and 72°N, *Nor. Geol. Tidsskr.*, *67*, 295–322.

Bukovics, C., and P. A. Ziegler (1985), Tectonic development of the mid-Norway continental margin:, *Mar. Pet. Geol.*, *2*, 2–22.

Caselli, F. (1987), Oblique-slip tectonics on the Mid-Norway Sheld, in *Petroleum Geology of the North European Margin*, edited by J. Brooks and K. Glennie, pp. 1049–1063, Graham and Trotman, Norwell, Mass.

Clark, A. H. (1989), Tectonothermal evolution of the western gneiss terrane and allochthonous Caledonian sequences, Senja, north Norway, M.S. thesis, 193 pp., Univ. of Ga., Athens.

Cobbold, P. R., and H. Quinuis (1980), Development of sheath folds in shear regimes, *J. Struct. Geol.*, *2*, 119–126.

Coker, J., M. G. Steltenpohl, A. Andresen, L. P. Gromet, and M. J. Kunk (1992), ^{40}Ar/^{39}Ar thermochronology and tectonic evolution of the Ofoten-Troms region, north Norwegian Caledonides, *Geol. Soc. Am. Abstr. Programs*, *24*, A235–A236.

Coker, J. E., M. G. Steltenpohl, A. Andresen, and M. J. Kunk (1995), An ^{40}Ar/^{39}Ar thermochronology of the the Ofoten-Troms region: Implications for terrane amalgamation and extensional collapse of the northern Scandinavian Caledonides, *Tectonics*, *14*, 435–447.

Coney, P. (1980), Cordilleran metamorphic core complexes-An overview, in *Cordilleran Metamorphic Core Complexes*, edited by M. Crittenden, P. Coney, and G. Davis, *Mem. Geol. Soc. Am.*, *153*, 7–31.

Copeland, P., and T. M. Harrison (1990), Episodic rapid uplift in the Himalaya revealed by ^{40}Ar/^{39}Ar analysis of detrital K-feldspar and muscovite, Bengal fan, *Geology*, *18*, 354–357.

Cumbest, R. J. (1987), Tectonothermal overprinting of the western gneiss terrane, Senja, Troms, northern Norway, M.S. thesis, 179 pp, Univ. of Georgia, Athens.

Cumbest, R. J., E. L. Johnson, and T. C. Onstott (1994), Argon composition of metamorphic fluids: Implications for ^{40}Ar/^{39}Ar geochronology, *Geol. Soc. Am. Bull.*, *106*, 942–951.

Currie, K. L., and M. A. J. Piasecki (1989), Kinematic model for southwestern Newfoundland based upon Silurian sinistral shearing, *Geology*, *17*, 938–941.

Dalland, A. (1975), The Mesozoic rocks of Andøy, northern Norway, *Nor. Geol. Unders.*, *316*, 271–287.

Dallmeyer, R. D., and A. Andresen (1992), Polyphase tectonothermal evolution of exotic Caledonian nappes in Troms, Norway: Evidence from ^{40}Ar/^{39}Ar mineral ages, *Lithos*, *29*, 19–42.

Dennis, A. J., and D. T. Secor (1987), A model for the development of crenulations in shear zones with applications from the southern Appalachian Piedmont, *J. Struct. Geol.*, *9*, 809–817.

Dewey, J. F., P. D. Ryan, and T. B. Andersen (1993), Orogenic uplift and collapse, crustal thickness, fabrics and metamorphic phase changes: The role of eclogites, in *Magmatic Processes and Plate Tectonics*, edited by H. M. Prichard et al., *Geol. Soc. Spec. Publ.*, *76*, 325–343.

Di Vincenzo, G., B. Ghiribelli, G. Giovanna, and R. Palmeri (2001), Evidence of a close link between petrology and isotope records; constraints from SEM, EMP, TEM and in situ ^{40}Ar-^{39}Ar laser analyses on multiple generations of white micas (Lanterman Range, Antarctica), *Earth Planet. Sci. Lett.*, *192*, 389–405.

Dunlap, W. J. (1997), Neocrystallization or cooling? ^{40}Ar/^{39}Ar ages of white micas from low-grade mylonites, *Chem. Geol.*, *143*, 181–203.

Dunlap, W. J., and H. Fossen (1998), Early Paleozoic orogenic collapse, tectonic instability, and late Paleozoic continental rifting revealed through thermochronology of K-feldspars, southern Norway, *Tectonics*, *17*, 604–620.

Dunlap, W. J., and A. K. Kronenberg (2001), Argon loss during deformation of micas: Constraints from laboratory deformation experiments, *Contrib. Mineral. Petrol.*, *141*, 174–185.

Eldholm, O. (1986), Formation of the Norwegian Sea, *Nature*, *319*, 360–361.

Flinn, D. (1985), The Caledonides of Shetland, in *The Caledonide Orogen-Scandinavia and Related Areas*, edited by D. G. Gee and B. A. Sturt, pp. 1159–1172, John Wiley, Hoboken, N. J.

Førseth, R. B., R. M. Macintyre, and J. Naterstad (1976), Mesozoic alkaline dykes in the Sunnhordland region, western Norway: Ages, geochemistry and regional significance, *Lithos*, *9*, 331–345.

Forslund, T. (1988), Post-Kaledonske forkastninger i Vest-Troms, med vekt pa Straumsbukta-Kvaløya-slettaforkastningen, Kvaløya, M. S. thesis, 169 pp., Univ. of Tromsø, Tromsø, Norway.

Fossen, H., and E. Rykkelid (1993), Reply to Comment on ''Postcollisional extension of the Caledonide orogen in Scandinavia: Structural expressions and tectonic significance'', *Geology*, *21*, 477–478.

Gee, D. G. (1975), A tectonic model for the central part of the Scandinavian Caledonides, *Am. J. Sci.*, *275A*, 468–515.

Gilotti, J. A. (1993), Discovery of a medium-temperature eclogite province in the Caledonides of north-east Greenland, *Geology*, *21*, 523–526.

Griffen, W. L., and P. N. Taylor (1978), Geology and age relations on Værøy, Lofoten, north Norway, *Bull. Nor. Geol. Unders.*, *338*, 71–82.

Griffen, W. L., P. N. Taylor, J. W. Hakkinen, K. S. Heier, I. K. Iden, E. J. Krogh, O. Malm, K. I. Olsen, D. E. Ormassen, and E. Tveten (1978), Archean and Proterozoic crustal evolution of Lofoten-Vesterålen, north Norway, *J. Geol. Soc. London*, *135*, 629–647.

Gromet, L. P., and A. Andresen (1993), U-Pb age constraints on Caledonian shear strain developed at the basement-allochthon contact, Ofoten region, Norway, *Eos Trans. AGU*, *74*(43), Fall Meet. Suppl., 123.

Grønlie, A., and D. Roberts (1989), Resurgent strike-slip duplex development along the Hitra-Snåsa and Verran faults, Møre-Trøndelag fault zone, central-Norway, *J. Struct. Geol.*, *11*, 295–305.

Hakkinen, J. W. (1977), Structural geology and metamorphic history of western Hinnøy and adjacent parts of eastern Hinnøy, North Norway, Ph.D. thesis, 161 pp., Rice Univ., Houston, Tex.

Hames, W. E. (1988), Timing and extent of Caledonian Orogeny within a portion of the western geniss terrane, Senja, northern Norway, M.S. thesis, 132 pp, Univ. of Georgia, Athens.

Hames, W. E., and A. Andresen (1996), Timing of Paleozoic orogeny and extension in the continental shelf of north-central Norway as indicated by laser ^{40}Ar/^{39}Ar muscovite dating, *Geology*, *24*, 1005–1008.

Hames, W. E., and J. T. Cheney (1997), On the loss of (super 40) Ar from muscovite during polymetamorphism, *Geochim. Cosmochim. Acta*, *61*, 3863–3872.

Harland, W. B., and R. A. Gayer (1972), The Arctic Caledonides and earlier oceans, *Geol. Mag.*, *109*, 289–314.

Hartz, E. H., and A. Andresen (1995), Caledonian sole thrust of central East Greenland: A crustal-scale Devonian extensional detachment?, *Geology*, *23*, 637–640.

Hodges, K. V. (1985), Tectonic stratigraphy and structural evolution of the Efjord-Sitasjaure area, northern Scandinavian Caledonides, *Bull. Nor. Geol. Unders.*, *399*, 41–60.

Hodges, K. V., J. M. Bartley, and B. C. Burchfiel (1982), Structural evolution of an A-type subduction zone, Lofoten Rombak area, northern Scandinavian Caledonides, *Tectonics*, *1*, 441–462.

Hodges, K. V., W. E. Hames, W. J. Olszewski, B. C. Burchfiel, L. H. Royden, and Z. Chen (1994), Thermobarometric and ^{40}Ar/^{39}Ar geochronologic constraints on Eohimalayan metamorphism in the Dinggye area, southern Tibet, *Contrib. Mineral. Petrol.*, *117*, 151–163.

Holloman, J. W. (1996), Structures, lithologies, and tectonic evolution of Røst, Lofoten, north Norway, M.S. thesis, 91 pp., Auburn Univ., Auburn, Ala.

Hutton, D. H. W., and M. McErlean (1991), Silurian and Early Devonian sinistral deformation of the Ratagain granite, Scotland: Constraints on the age of Caledonian movements on the Great Glen fault system, *Geol. Mag.*, *148*, 1–4.

Jørgensen, F., and T. Navrestad (1981), The geology of the Norwegian shelf between 62°N and the Lofoten Islands, in *Petroleum Geology of the Continental Shelf of NW Europe*, edited by L. V. Illing and G. D. Hobson, pp. 407–413, Inst. of Pet. Geol., London.

Klein, A. (1997), Geology of the Leknes group and underlying basement in west-central Vestvågøy, north Norway, M.S. thesis, 171 pp, Auburn Univ., Auburn, Ala.

Klein, A., and M. G. Steltenpohl (1999), Basement-cover relations and late- to post-Caledonian extension in the Leknes group, west-central Vestvågøy, Lofoten, north Norway, *Nor. Geol. Tidsskr.*, *79*, 19–31.

Klein, A., M. G. Steltenpohl, W. E. Hames, and A. Andresen (1999), Ductile and brittle extension in the southern Lofoten archipelago, north Norway: Implications for differences in tectonic style along an ancient collisional margin, *Am. J. Sci.*, *299*, 69–89.

Løseth, H., and E. Tveten (1996), Post-Caledonian structural evolution of the Lofoten and Vestrålen offshore and onshore areas, *Norsk Geol. Tidsskr.*, *76*, 215–230.

MacCready, T., A. W. Snoke, J. E. Wright, and K. A. Howard (1997), Mid-crustal flow during Tertiary extension in the Ruby Mountains core complex, Nevada, *Geol. Soc. Am. Bull.*, *109*, 1576–1594.

McKinney, J. B. (1989), Precambrian and Caledonian evolution of portions of the western gneiss terrane and Senja nappe, Troms, northern Norway, M.S. thesis, 201 pp, Univ. of Georgia, Athens.

Mjelde, R., M. A. Sellevoll, H. Shimamura, T. Iwasaki, and T. Kanazawa (1993), Crustal structure beneath Lofoten, N. Norway, from vertical incidence and wide-angle seismic data, *Geophys. J. Int.*, *114*, 116–126.

Mjelde, R., S. Kodaira, and M. A. Sellevoll (1996), Crustal structure of the Lofoten margin, N. Norway, from normal incidence and wide-angle seismic data: A review, *Nor. Geol. Tidsskr.*, *76*, 187–198.

Mooney, L. J. (1997), Lithologies, structures, and metamorphic development of Værøy, Lofoten archipelago, north Norway, M.S. thesis, 108 pp., Auburn Univ., Auburn, Ala.

Neuman, E. R., K. H. Olesen, W. S. Baldridge, and B. Sundvoll (1992), The Oslo rift: A review, *Tectonophysics*, *208*, 1–18.

Norton, M. G. (1986), Late Caledonide extension in western Norway: A response to extreme crustal thickening, *Tectonics*, *5*, 195–204.

Northrup, C. J. (1996), Structural expressions and tectonic implications of general non-coaxial flow in the midcrust of a collisional orogen: The northern Scandinavian Caledonides, *Tectonics*, *15*, 490–505.

Northrup, C. J. (1997), Timing structural assembly, metamorphism, and cooling of Caledonian Nappes, Ofoten-Efjorden, north Norway: Tectonic insights from U-Pb and ^{40}Ar/^{39}Ar geochronology, *J. Geol.*, *105*, 565–582.

Olesen, O., and J. F. Dehls (2001), A low-density mantle below the Sarek-Vestfjorden area, northern Scandinavia—Evidence of a mantle convection driven by Late Cenozoic uplift?, paper presented at Geonytt Norsk Geologisk Forenings XVII Vinterkonferanse, Norsk Petroleumsforening, Oslo, 8–10 Jan.

Olesen, O., T. H. Torsvik, E. Tveten, K. B. Zwann, H. Løseth, and T. Henningsen (1997), Basement structure of the continental margin in the Lofoten Lopphavet area, northern Norway: Constraints from potential field data, on-land structural mapping and palaeomagnetic data, *Nor Geol. Tidsskr.*, *77*, 15–30.

Osmundsen, P. T., and T. B. Andersen (1994), Caledonian compressional and late-orogenic extension in the Stavenes area, Sunnfjord, western Norway, *J. Struct. Geol.*, *16*, 1385–1401.

Roberts, D., and D. G. Gee (1985), An introduction to the structure of the Scandinavian Caledonides, in *The Caledonide Orogen-Scandinavia and Related Areas*, edited by D. G. Gee and B. A. Sturt, pp. 55–68, John Wiley, Hoboken, N. J.

Robinson, P. (1991), Comparative tectonics of the Hinterland regions of the Scandian orogen, central Norway and the Acadian orogen, southern New England, USA: Terranes in the Arctic Caledonides, *Terra Abstr.*, *4*, 27.

Rønnevik, H., and T. Navrestad (1977), Geology of the Norwegian shelf between 62°–69°N, *GeoJ.*, *1*, 33–46.

Royden, L., and K. V. Hodges (1984), A technique for analyzing the thermal and uplift histories of eroding orogenic belts: A Scandinavian example, *J. Geophys. Res.*, *89*, 7091–7106.

Rykkelid, E. (1992), Contractional and extensional structures in the Caledonides, Dr.Sci. thesis, 176 pp., Univ. of Oslo, Oslo, Norway.

Rykkelid, E., and A. Andresen (1994), Late Caledonian extension in the Ofoten area, northern Norway, *Tectonophysics*, *231*, 157–169.

Seranne, M., and M. Seguret (1987), The Devonian basins of western Norway: Tectonics and kinematics of an extending crust, in *Continental Extensional Tectonics*, edited by M. P. Coward, J. F. Dewey, and P. L. Hancock, *Geol. Soc. Spec. Publ.*, *28*, 537–548.

Sherlock, S. C. (2001), Two-stage erosion and deposition in a continental margin setting: An ^{40}Ar/^{39}Ar laserprobe study of offshore detrital white micas in the Norwegian Sea, *J. Geol. Soc. London*, *158*, 793–799.

Sigmond, E. M. O., M. Gustavson, and D. Roberts (1984), Bedrock map of Norway, scale 1:1 million, Nor. Geol. Unders., Trondheim.

Sigmond, E. M. O. (1992), Bedrock map of Norway and adjacent ocean areas, scale 1:3 million, Nor. Geol. Unders., Trondheim.

Spear, F. S., and J. T. Cheney (1989), A petrogenetic grid for pelitic schists in the system SiO_2 - Al_2O_3 - FeO- MgO - K_2O - H_2O, *Contrib. Mineral. Petrol.*, *101*, 149–164.

Steltenpohl, M. G. (1987), Tectonostratigraphy and tectonic evolution of the Skønland area, north Norway, *Bull. Nor. Geol. Unders.*, *409*, 1–20.

Steltenpohl, M. G., and J. M. Bartley (1987), Thermobarometric profile through the Caledonian nappe stack of western Ofoten, north Norway, *Contrib. Mineral. Petrol.*, *96*, 93–103.

Steltenpohl, M. G., and J. M. Bartley (1988), Crossfolds and Back-folds in the Ofoten-Tysfjord area, north Norway, and their significance for Caledonian tectonics, *Geol. Soc. Am. Bull.*, *100*, 140–151.

Steltenpohl, M. G., and J. M. Bartley (1993), Comment on "Postcollisional extension of the Caledonide orogen in Scandinavia: Structural expressions and tectonic significance", *Geology*, *21*, 476–477.

Sturt, B. A., A. Dalland, B. Mitchell, and J. L. Mitchell (1979), The age of the sub Mid-Jurassic tropical weathering profile of Andøya, northern Norway, and the implications for the late Palaeozoic palaeography in the North Atlantic region, *Geol. Rundsch.*, *68*, 523–542.

Talwani, M., and O. Eldholm (1977), Evolution of the Norwegian-Greenland Sea, *Geol. Soc. Am. Bull.*, *88*, 969–999.

Tilke, P. G. (1986), Caledonian structure, metamorphism, geochronology, and tectonics of the Sitas-Singas area, Sweden, Ph.D. thesis, 295 pp., Mass. Inst. of Technol., Cambridge.

Torsvik, T. H., B. A. Sturt, E. Swensson, T. B. Andersen, and J. F. Dewey (1992), Paleomagnetic dating of fault rocks: Evidence for Permian and Mesozoic movements and brittle deformation along the extensional Dalsfjord fault, western Norway, *Geophys. J. Int.*, *109*, 565–580.

Torsvik, T. H., T. B. Andersen, E. A. Eide, and H. J. Walderhaug (1997), The age and tectonic significance of dolerite dykes in western Norway, *J. Geol. Soc. London*, *154*, 961–973.

Tucker, R. D., R. Boyd, and S. Barnes (1990), A U-Pb zircon age for the Råna intrusion, N. Norway: New evidence of basic magmatism in the Scandinavian Caledonides in Early Silurian time, *Nor. Geol. Tidsskr.*, *70*, 229–239.

Tull, J. F. (1977), Geology and structure of Vestvågøy, Lofoten, north Norway, *Bull. Nor. Geol. Unders.*, *333*, 59 pp.

Tull, J. F. (1978), Geology and structure of Vestvågøy, Lofoten, north Norway, *Skr. Nor. Geol. Unders.*, *42*, 109 pp.

Tull, J. F., J. M. Bartley, K. V. Hodges, A. Andresen, M. G. Steltenpohl, and J. M. White (1985), The Caledonides in the Ofoten region (68–69N), north Norway: Key aspects of tectonic evolution, in *The Caledonide Orogen-Scandinavia and Related Areas*, edited by D. G. Gee and B. A. Sturt, pp. 553–569, John Wiley, Hoboken, N. J.

Van der Voo, R., and C. Scotese (1981), Paleomagnetic evidence for large (c. 2000 km) sinistral offset along the Great Glenn fault during the Carboniferous, *Geology*, *9*, 583–589.

Van Winkle, S. W., M. G. Steltenpohl, and A. Andresen (1996), Basement-cover relations and Caledonian tectonostratigraphy of Sandsøya, Grytøya, Åkerøya, and Kjøtta, Western Gneiss Region, north Norway, *Bull. Nor. Geol. Unders.*, *431*, 67–89.

Waltman, C. K. (1997), Geological investigations into the tectonic evolution of the Scandinavian Caledonides: Lofoten, north Norway, M.S. thesis, 111 pp., Auburn Univ., Auburn, Ala.

Wernicke, B. (1985), Uniform-sense simple shear of the continental lithosphere, *Can. J. Earth Sci.*, *22*, 108–125.

West, D. P., Jr., and D. R. Lux (1993), Dating mylonitic deformation by the ^{40}Ar-^{39}Ar method; an example from the Norumbega fault zone, Maine, *Earth Planet. Sci. Lett.*, *120*, 221–237.

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