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An $^{40}Ar/^{39}Ar$ thermochronology of the Ofoten-Troms region: Implications for terrane amalgamation and extensional collapse of the northern Scandinavian Caledonides

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Abstract. Fifteen $^{40}Ar/^{39}Ar$ cooling ages are reported for metamorphic hornblende and muscovite from far traveled terranes constituting the Ofoten nappe stack of northern Norway. Eight cooling ages on hornblende range from 425 to 394 Ma and seven muscovite ages, from the same or nearby outcrops as the hornblendes, range from 400 to 373 Ma. These data are compared with $^{40}Ar/^{39}Ar$ ages from over a large part of the northern Caledonides to evaluate regional mineral cooling patterns. Results indicate that (1) Scandian (Silurian-Devonian) metamorphism was predominant; (2) most of the nappes investigated contain some vestige of pre-Scandian tectonism and/or metamorphism; (3) hornblende and muscovite cooling ages are progressively younger to the west and south, which suggests a hinged-to-the-east mineral cooling pattern; and (4) a late, out-of-sequence thrust is the only disruption of this cooling pattern. Synmetamorphic amalgamation of the nappes resulted from Scandian A type subduction. The hinged-to-the-east mineral cooling pattern implies isostatic adjustment and exhumation of the footwall of a west dipping, crustal-scale extensional fault, located somewhere west of the present Norwegian coast, during late synorogenic gravitational collapse. The late out-of-sequence fault formed contemporaneously with uplift in the hinterland, implying a kinematic and temporal connection with east directed contractional faulting in the foreland.

Introduction

The Caledonides are long known to be a classic thrust-dominated orogen comprising thin, vertically stacked, areally extensive (hundreds of kilometers), far traveled nappes emplaced during the Silurian collision of Baltica and Laurentia. Cross orogenic culminations and deeply incised glacial valleys provide excellent exposure of the Baltic Precambrian basement and its overlying stacked terranes at all preserved tectonostratigraphic levels. Relatively few absolute age data are reported for the northern part of the Caledonides, however, and consequently our understanding about the timing of structural/metamorphic events is limited. Our argon isotopic studies are aimed at addressing three particular problems concerning the tectonic evolution of this segment of the belt. First, there is debate as to the sequence and timing of nappe emplacement and the crustal level(s) at which stacking took place [*Barker*, 1984; *Steltenpohl and Bartley*, 1987; *Anderson et al.*, 1992]. Second, absolute age determinations and fossil evidence from throughout the Caledonides indicate that the main phase of Caledonian deformation and metamorphism, the Scandian phase [*Gee*, 1975], took place during the Late Silurian-Early Devonian, but pre-Scandian, Cambrian-Ordovician or earlier tectonometamorphic relics are also found. Pre-Scandian effects are well known in the terranes of Baltic affinity [*Andréasson*, 1994] but there is debate as to the nature, extent and distribution of such effects in the outboard terranes [*Barker*, 1989; *Andresen and Steltenpohl*, 1991, 1994; *Andréasson*, 1994; *Stephens et al.*, 1993]. Third, to date, workers in the northern Caledonides have focused mainly on the contractional history of this part of the orogen and, as a consequence, it is not yet known how or whether structures here can be related to the phenomenal extensional event documented in the area of the Devonian basins of southwest Norway, 800 km to the south [*Norton*, 1986; *Séranne and Séguret*, 1987; *Andersen and Jamtveit*, 1990; *Fossen and Rykkelid*, 1992, 1993; *Steltenpohl and Bartley*, 1993]. Results provide new information on each of these problems and, significantly, they elucidate regional mineral-cooling patterns that constrain the style of Early Devonian extension in the northern Caledonides. Our interpretation of this extensional event is similar to that described for southwest Norway and it invokes foreland-directed movement [*Andersen et al.*, 1991; *Dewey et al.*, 1993; *Fossen*, 1993; *Andersen*, 1993; *Sjøstrøm and Bergman*, 1994], which we believe has general significance for collisional orogenic belts.

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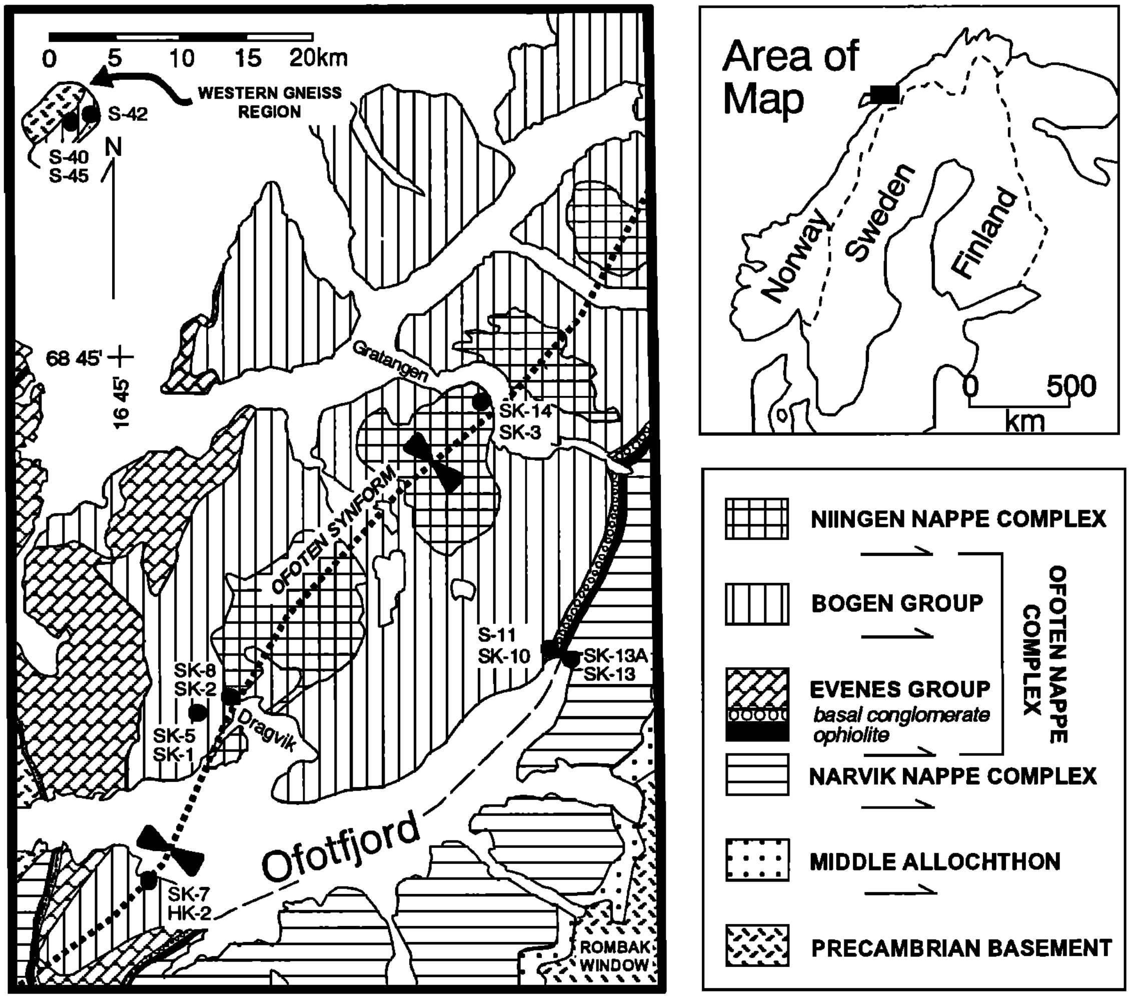

Figure 1. Generalized tectonic map of the Ofoten area (modified from *Gustavson* [1972], *Steltenpohl* [1987], and *Andresen and Steltenpohl* [1994]) illustrating argon sample localities.

Geologic Setting

Caledonian nappes in Ofoten are exposed as a composite klippe in the core of the shallow northeast plunging Ofoten synform [*Gustavson*, 1972] (Figures 1 and 2). The Ofoten synform is a post nappe assembly structure that provides a near complete cross section from the Precambrian Baltic basement exposed in the Rombak window upward through the highest preserved units in this part of the Caledonides. Structurally overlying the Precambrian basement, from bottom to top, are units of the Middle, Upper (Narvik and Ofoten nappe complexes), and Uppermost (Niingen nappe complex) Allochthons [*Andresen and Steltenpohl*, 1994]. The tectonostratigraphy of this region has been described by *Andresen et al.* [1985], *Tull et al.* [1985], *Barker* [1986], and *Andresen and Steltenpohl* [1991, 1994].

Granitic gneisses of the Baltic basement are nonconformably overlain by late Proterozoic (Riphean and Vendian) to Silurian platformal miogeoclinal sedimentary rocks. These units occur in Ofoten as structurally imbricated, greenschist-facies rocks of the Lower and Middle Allochthons [*Roberts and Gee*, 1985; *Björklund*, 1987].

The upper contact of the Middle Allochthon marks the boundary between rocks of Baltic affinity and the exotic terranes of the overlying Upper Allochthon. The lowest tectonostratigraphic units of the Upper Allochthon include the Høgtind Nappe of *Barker* [1986] (Køli Nappe of southern Norway and Sweden [*Gee*, 1978]) and the Narvik nappe complex [*Steltenpohl and Andresen*, 1991]. The Narvik nappe complex contains multiple internal thrust sheets comprising complexly interleaved kyanite-grade schists and gneisses [*Hodges et al.*, 1982; *Crowley*, 1985; *Barker*, 1986; *Tilke*, 1986]. Sheared mafic and ultramafic rocks have been interpreted to be fragments of obducted oceanic crust [*Hodges et al.*, 1982; *Boyd*, 1983; *Crowley*, 1985].

Overlying the Narvik nappe complex is the Ofoten nappe complex, which contains a fragmented ophiolite (Lillevik ophiolite fragment [*Boyd*, 1983]) near its base [*Andresen and Steltenpohl*, 1994]. This fragmented ophiolite corresponds to the Lyngen ophiolite of Troms [*Minsaas and Sturt*, 1985;

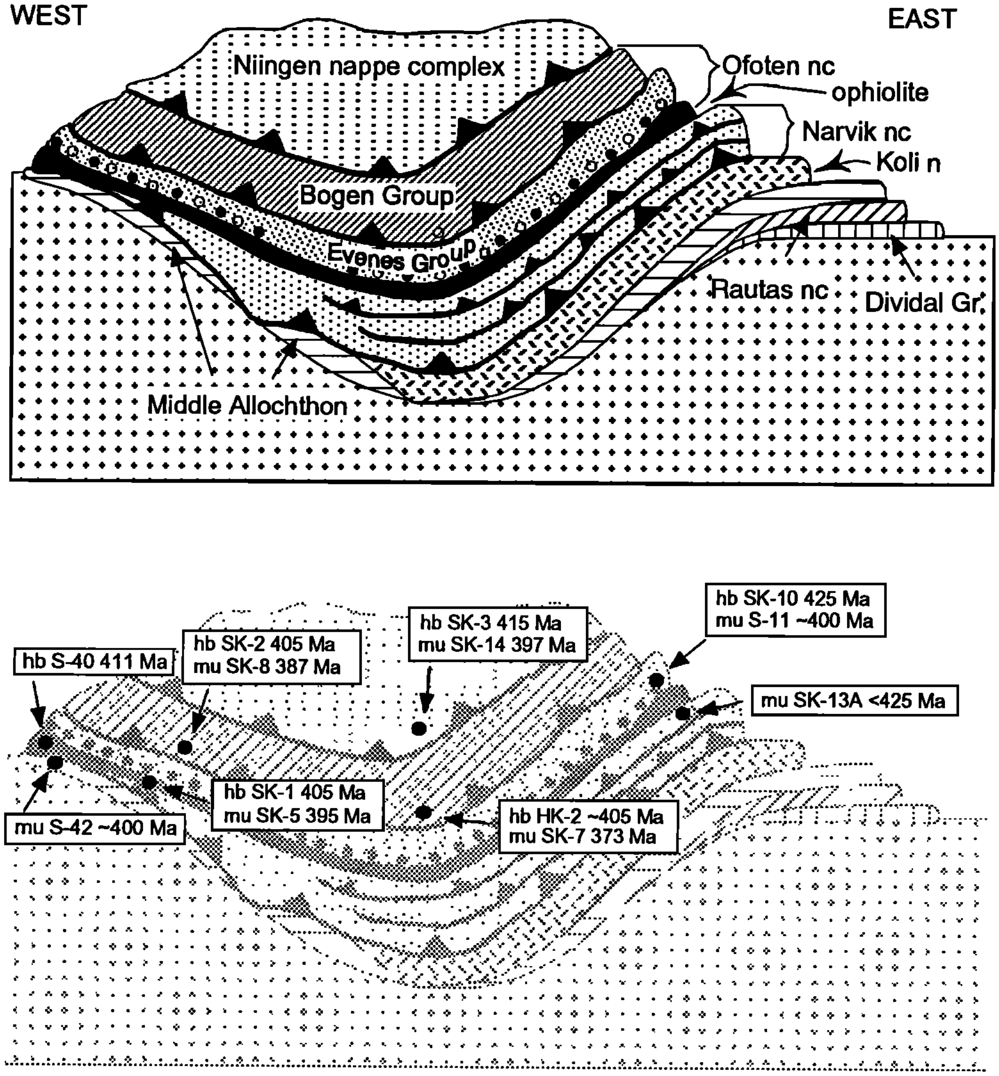

Figure 2. (top) Simplified cross section of the Ofoten nappe stack (modified from *Andresen and Steltenpohl* [1994]). (bottom) Spatial relations of $^{40}Ar/^{39}Ar$ mineral ages projected onto the cross section.

Steltenpohl et al., 1990; *Andresen and Steltenpohl*, 1991, 1994], which is the largest ophiolite complex in Scandinavia. A regional unconformity separates the Lyngen ophiolite from overlying rocks of the Balsfjord Group. Halysitid corals recovered from the Balsfjord Group, which are of unusually low metamorphic grade for the Upper Allochthon, indicate an upper Llandoverian age [*Binns and Matthews*, 1981; *Björlykke and Olaussen*, 1981], constraining a minimum age for the unconformity. In Ofoten, 150 km south, Ofoten nappe complex units overlying the basal ophiolite correlate with the Balsfjord Group [*Steltenpohl et al.*, 1990] and are called the Evenes and Bogen Groups (Salangen Group of *Gustavson* [1966]). The Evenes Group contains metasedimentary rocks of variable metamorphic grade, from chlorite zone up to kyanite zone. Multiple felsic intrusives occur within the Bogen Group schists and gneisses but are lacking in the underlying Evenes Group [*Steltenpohl*, 1987; *Steltenpohl et al.*, 1988]. A synmetamorphic thrust marks the boundary between the Bogen Group and the overlying migmatitic schist- and gneiss-dominated Niingen nappe complex (Uppermost Allochthon). Several internal thrust sheets appear within the Niingen nappe complex [*Karlsen*, 1988; *Andresen and Steltenpohl*, 1994]. Large, kilometer-scale mafic/ultramafic bodies within the lower parts of the Niingen nappe complex are interpreted as fragmented ophiolitic material [*Boyd*, 1983; *Barker*, 1986; *Steltenpohl*, 1987].

Four deformational phases are distinguished in the Ofoten nappes [*Bartley*, 1984; *Hodges*, 1985; *Steltenpohl*, 1987], the first two of which formed under early-phase, pre-amphibolite to synamphibolite-facies conditions, and the second two of which formed under late-phase, postmetamorphic peak, greenschist-facies conditions. Early-phase, east vergent recumbent folds deform com-positional layering and mineral foliation formed prior to and during the metamorphic peak. Structures that predated the metamorphic peak are obscure due to near complete obliteration. The early-phase structures are deformed by late-phase, east plunging crossfolds and northwest vergent, northeast plunging backfolds. Differences in the structural histories of the allochthons are not recognized. Early-phase structures are considered to reflect preaccretionary and synaccretionary events, whereas late-phase structures reflect postaccretionary modification of the stack of terranes.

Previous Geochronology and Age Constraints

Hodges [1982] reported conventional K-Ar ages of 436±36 Ma and 448±40 Ma for hornblende from the Narvik nappe complex. These ages are considerably older than $^{40}Ar/^{39}Ar$ hornblende ages reported by *Tilke* [1986] and *Anderson et al.* [1992], probably due to the inability to distinguish the effects of extraneous argon using the conventional K-Ar technique [*Hodges*, 1985]. *Tilke* [1986], however, also reported a 496 Ma $^{40}Ar/^{39}Ar$ hornblende age from a unit within the Narvik nappe complex, which he interpreted as a relic from a pre-Scandian thermal event. The Narvik nappe complex corresponds to the Nordmannvik nappe of northern Troms, which contains 492 Ma granodiorites [*Elvevold*, 1987]. *Tucker et al.* [1990] presented a U-Pb zircon age of 437+1/-2 Ma for emplacement of the prekinematic Råna massif, which intrudes rocks of the Narvik nappe complex. The same authors interpret this age to reflect the time of igneous crystallization of the Råna mafic and ultramafic cumulates, which were emplaced in a marginal basin or back arc setting. The intrusion thus places a maximum on the age of metamorphism for this Narvik nappe complex thrust sheet. Late Ordovician-Early Silurian fossils within the Balsfjord/Evenes and Bogen Groups [*Steltenpohl et al.*, 1990] document Scandian metamorphism within these thrust sheets. Because the Upper Ordovician Evenes Group unconformably overlies the ophiolite, the ophiolite itself must be pre-Early Ordovician in age. *Lindstrøm* [1988] presented an Rb/Sr whole-rock isochron age of 427±6 Ma for the syntectonic Dragvik granite, which is a stitching pluton crosscutting the thrust between the Ofoten and Niingen nappe complexes [*Steltenpohl*, 1987]. Monazites from synkinematic intrusive pods from the base of the Niingen nappe complex have an U-Pb crystallization age of circa 430 Ma [*Coker et al.*, 1992].

Analytical Results for $^{40}Ar/^{39}Ar$

Analyses for $^{40}Ar/^{39}Ar$ were performed on hornblende, muscovite, and biotite samples collected at various structural levels of the Ofoten nappe stack (Figures 1 and 2). Incremental $^{40}Ar/^{39}Ar$ release spectra of hornblende and muscovite are presented in Figures 3 and 4, respectively. Analytical methods, tabulated results, and sample locality descriptions are in an appendix[1].

Hornblende. Eight hornblende separates were obtained from amphibolites within the Narvik (Sk-13), Ofoten (Sk-1, Sk-2, Sk-10, Hk-2, S-40, S-45), and Niingen (Sk-3) nappe complexes. The amphibole concentrates display variably discordant apparent age spectra and no plateaus were defined (Figure 3). Apparent K/Ca ratios are flat, generally indicating clean separates. Hornblendes from throughout the Caledonides are known to contain extraneous argon, which results in disturbed saddle-shaped spectra such that plateau ages are rare [*Hodges*, 1985; *Lux*, 1985; *Tilke*, 1986; *Dallmeyer*, 1988]. Contamination by nonatmospheric extraneous ^{40}Ar in Norwegian amphiboles has been attributed to upward diffusion of ^{40}Ar released from minerals lower in the crust following a short high-temperature interval [*Tilke*, 1986]. Other sources of extraneous argon may be intracrystalline inclusions of ^{40}K bearing phases not reset during metamorphism, fluid inclusions, uptake of intergranular radiogenic argon by the crystal and intracrystalline compositional zonation [*McDougall and Harrison*, 1988; *Dallmeyer and Andresen*, 1992]. *Tilke* [1986] demonstrated that $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ correlation plots, when used in conjunction with the minimum age heating step within a saddle-shaped spectrum that contains numerous heating increments, provide geologically consistent and reliable cooling ages. A similar treatment has been applied to some of the hornblende spectra presented herein. Criteria for reliable correlation ages for the purpose of this study are (1) that there is a mean standard weighted deviation (MSWD) of less than 2.5 [*Kunk et al.*, 1994], (2) that there is a correlation age younger than or equal to the apparent age of the saddle minimum increment, (3) that a substantial amount of gas must have evolved for the increments to which correlation is applied, and (4) that the age must be reasonably older than the age determined for muscovite analyzed from the same or nearby rock sample.

Muscovite. Seven muscovite separates were obtained from the Middle Allochthon (S-42), Narvik (Sk-13A), Ofoten (Sk-5, Sk-7, Sk-8, and S-11), and Niingen (Sk-14) nappe complexes (Figure 4). Muscovite samples were collected from the same rocks or outcrops as their hornblende counterparts in order to evaluate the cooling path between closure of the two mineral species. In contrast to the hornblende spectra, four of the muscovite samples (Sk-5, Sk-7, Sk-8, and Sk-14) define plateau ages.

Biotite. Five biotite separates taken from the same localities as the muscovite samples, S-42, S-11, Sk-13A, Sk-5, and Sk-14, were fused and the gas analyzed as a single step. The total fusion ages are analogous to conventional K-Ar ages excepting minor variations in analytical techniques and a better analytical precision [*Dalrymple and Lanphere*, 1971]. Biotite commonly produces flat release patterns that reflect anomalously old ages [*McDougall and Harrison*, 1988]. Because the temperature for biotite closure is below that of muscovite closure, biotite samples should yield slightly lower ages than muscovites from the same localities. For four of the five Ofoten samples, the biotite age was considerably older than the age determined by incremental release of their muscovite counterparts, indicating the presence of extraneous argon in the biotite. The total fusion ages obtained from these samples therefore are considered to be geologically meaningless. Biotite sample Sk-14,

[1]Appendix is available with entire article on microfiche. Order from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009. Document T94-003; $2.50. Payment must accompany order.

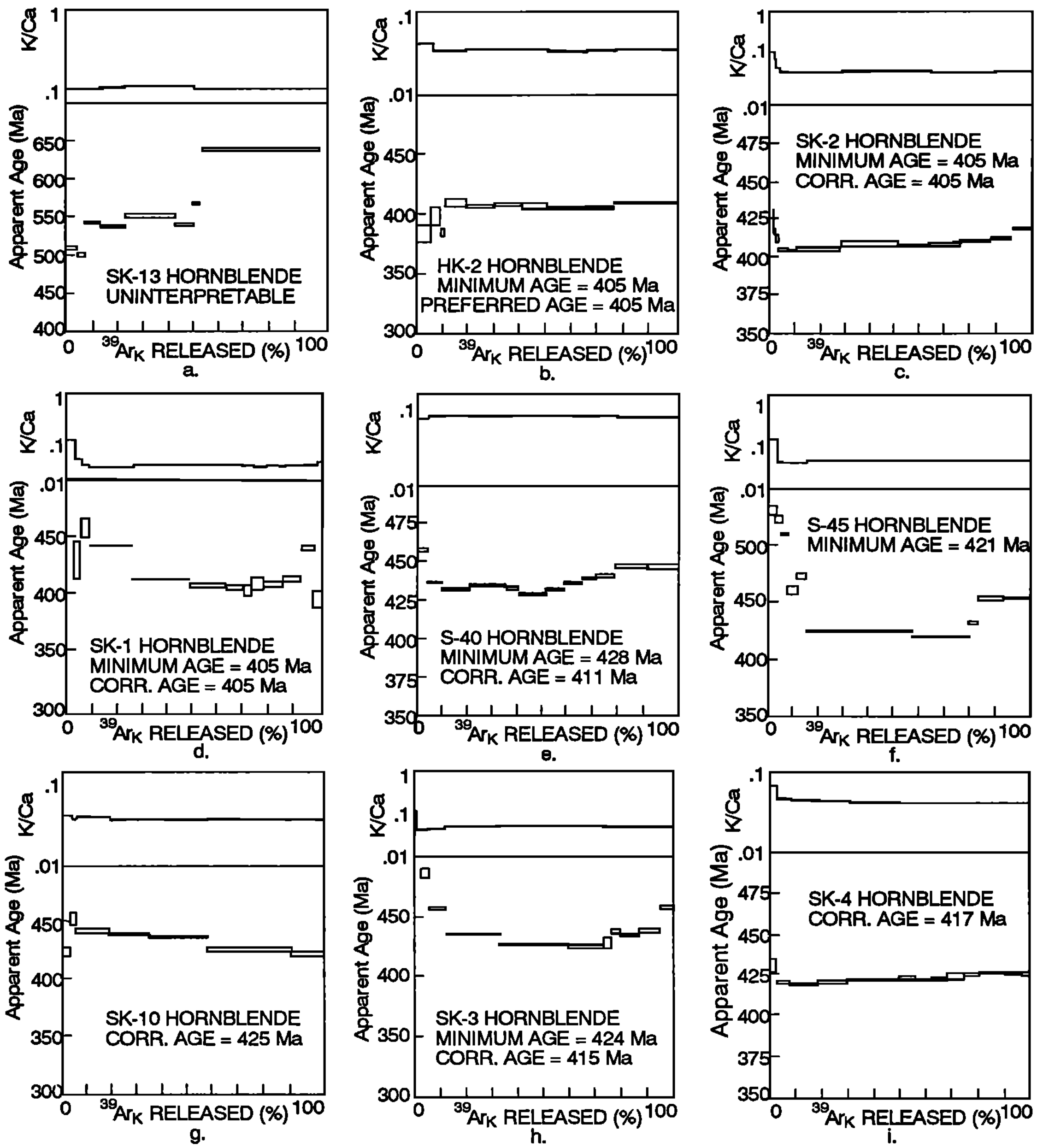

Figure 3. Hornblende age spectra from the Ofoten region. See Figure 1 for sample locations.

however, yielded a total gas age of 394 Ma, 3 m.y. younger than its muscovite counterpart Sk-14. This sample is thought to contain extraneous argon because it is considerably older than other biotite age determinations from the Ofoten area, based on conventional K-Ar, Rb-Sr biotite-whole rock, and $^{40}Ar/^{39}Ar$ methods [*Crowley*, 1985; *Tilke*, 1986].

Interpretation

Plateau ages for muscovite and correlation ages for hornblende are interpreted to date the latest cooling below the temperature required for intracrystalline retention of argon after the last metamorphic event that affected the rock. The closure temperature for hornblende appears to be dependent on the rate of cooling. *Harrison and McDougall* [1981] suggested a closure temperature of 540±40°C for hornblendes cooling at a rate of >100°C/ m.y., however, *Harrison* [1981] suggested temperatures between 480°C and 500°C for hornblende closure in slowly cooling metamorphic terranes. Most workers agree that the closure temperature for muscovite is approximately 350°C [*Purdy and Jäger*, 1976; *Cliff and Cohen*, 1980; *Harrison and McDougall*, 1981; *Dallmeyer*, 1988]. *Dallmeyer and Andresen* [1992], however, in an application of experimental data from *Robbins* [1972] to diffusive equations of *Dodson* [1973], stated that temperatures of 375°C may be more appropriate. In this report, we use 500°C and 350°C as the closure temperatures for hornblende and muscovite, respectively.

Steltenpohl [1987] interpreted the Ofoten nappe stack to have formed as a foreland-younging, piggyback thrust sequence in which the structurally highest Niingen nappe

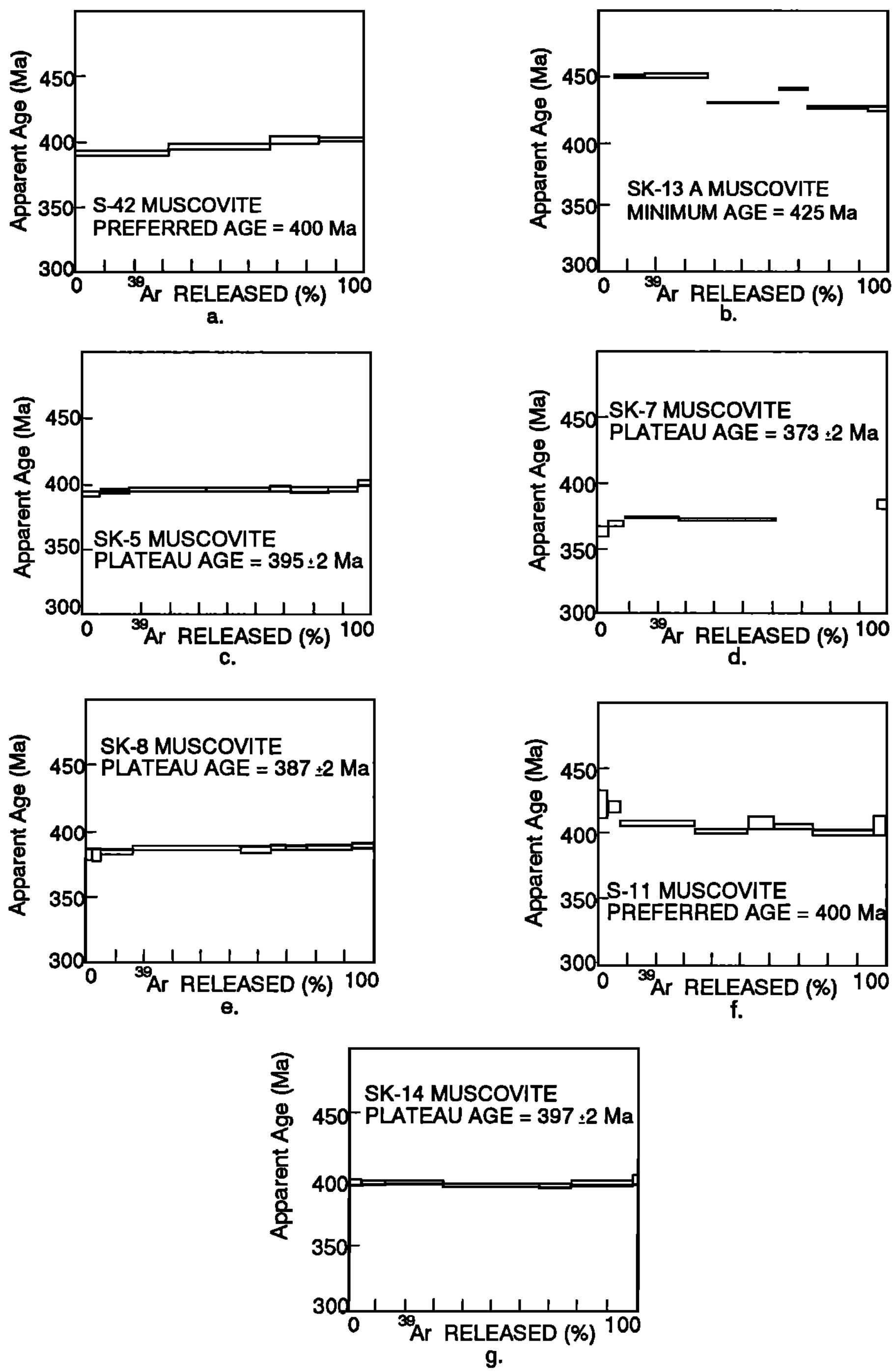

Figure 4. Muscovite age spectra from the Ofoten region. See Figure 1 for sample locations.

complex is the farthest traveled nappe. Metamorphic hornblende and muscovite from the Niingen nappe complex have a $^{36}Ar/^{40}Ar$ versus $^{40}Ar/^{39}Ar$ correlation age of 415 Ma and a plateau age of 397$\pm$2 Ma, respectively. The younger age of the muscovite plateau supports the correlation age on the hornblende. These cooling ages are compatible with cooling from a Scandian metamorphic peak, which may be approximated by the 430 Ma crystallization age of synmetamorphic intrusive pods within migmatitic schists near the base of this nappe [*Coker et al.*, 1992]. The ophiolitic rocks along the base of the Niingen nappe complex imply that an ocean basin of unknown size was consumed during its emplacement upon the Ofoten nappe complex, making this a potentially important tectonic boundary.

The 427 Ma synkinematic Dragvik granite [*Lindstrøm*, 1988] that stitches the synmetamorphic thrust between the

Niingen nappe complex and underlying Bogen Group of the Ofoten nappe complex [*Steltenpohl*, 1987] requires that the thrust formed prior to or close to 427 Ma, consistent with the suggested timing of the thermal peak within rocks of the Niingen nappe complex. The Evenes Group structurally underlies the Bogen Group but contains no felsic intrusives, indicating that juxtaposition of the Niingen-Bogen composite allochthon upon the Evenes Group occurred after the intrusion of the Dragvik granite. Ofoten nappe complex hornblendes have cooling ages that range from 424 to 404 Ma, whereas muscovites range from 395 to 373 Ma with three plateau ages spanning the same range. These ages record cooling following Late Silurian-Early Devonian Scandian metamorphism, which is required by the presence of Early Silurian fossils within the Balsfjord Group. *Sutter et al.* [1985] reported that the first separable hornblendes from a prograde metamorphic sequence that crystallized near or within the staurolite-garnet zone can be used to date the thermal maximum because they formed near to the temperature conditions of argon closure in hornblende (~500°C). Hornblende Sk-10 comes from what appears to be the highest grade rocks (staurolite-garnet zone) from the variable metamorphic grade units of the Evenes Group in Bjerkvik. The 425 Ma correlation age of Sk-10, which is the oldest age determined in our study, is therefore considered to approximate the time of the thermal peak for these units. Combined with the Early Silurian fossils, this is the best constraint on the time of metamorphism of the Ofoten nappe complex.

Although the absolute age of the ophiolite fragments at the base of the Ofoten nappe complex is undetermined, the well-documented occurrence of Early Ordovician ophiolites elsewhere in the Caledonides and the presence of Late Ordovician-Early Silurian faunas in the stratigraphically overlying Balsfjord Group are consistent with concomitant formation (circa 495-475 Ma [*Pedersen and Furnes*, 1991; *Pedersen*, 1992]). Clasts of ophiolitic material in the conglomerate at the base of the Evenes/Balsfjord Group do not indicate metamorphism prior to conglomerate deposition [*Steltenpohl et al.*, 1990]. The 411 Ma cooling age on hornblende S-40 from the ophiolite complex is consistent with cooling following Scandian metamorphism. The ophiolite had already been obducted, uplifted, and eroded by the Middle Ordovician, however, and thus the Ofoten nappe complex contains pre-Scandian relics.

The simple piggyback thrust interpretation of the Ofoten nappe stack must be modified in order to accommodate the late, postmetamorphic fault recently recognized along the base of the Ofoten nappe complex [*Andresen and Steltenpohl*, 1991; *Anderson et al.*, 1992]. The hanging wall to this fault can be interpreted in terms of nearly upright cooling with a hinge located toward the east. The Niingen nappe complex cooled through the 500°C and 350°C isotherms earliest (415 and 397 Ma, respectively), followed by the westernmost areas (411 and ~400 Ma, respectively), then the more central parts of the Ofoten synform (405 and 387 Ma, respectively), and finally the deeper structural levels exposed in the synform's hinge zone (405 and 373 Ma, respectively). If this pattern continued structurally downward, then the Narvik nappe complex should contain the youngest cooling ages. Although hornblende sample Sk-13 was uninterpretable, *Anderson et al.* [1992] reported a near-concordant amphibole spectrum with a plateau age of 425±3 Ma from a Narvik nappe complex amphibolite that crops out less than 100 m south of our locality. The circa 425 Ma maximum age for muscovite sample SK-13A is compatible with this date. *Tilke* [1986] reported a circa 432 Ma hornblende from the Narvik nappe complex farther south of our study area. The Narvik nappe complex thus contains the oldest reported Scandian cooling ages and documents that cooling of these units through hornblende closure temperature occurred earlier than in the structurally higher nappes. The fault at the base of the Ofoten nappe complex therefore has the geometry of an out-of-sequence, east directed thrust. In addition, the Narvik nappe complex contains an obscure pre-Scandian history because Early Ordovician $^{40}Ar/^{39}Ar$ hornblende cooling ages are reported [*Tilke*, 1986], Ordovician plutons occur in correlative units in Troms [*Elvevold*, 1987], and petrographic and thermobarometric data document the presence of metamorphic relics formed prior to the formation of the main Scandian schistosity [*Steltenpohl and Bartley*, 1987; *Andresen and Steltenpohl*, 1991].

Discussion

Previously reported $^{40}Ar/^{39}Ar$ data on hornblende and muscovite samples from the Ofoten-Troms region, reported by *Tilke* [1986], *Dallmeyer and Andresen* [1992], and *Anderson et al.* [1992], combine with the results of the present study to elucidate regional patterns of metamorphic cooling. A compilation of these data is presented in Figures 5 and 6. An additional hornblende analysis from near Tromsö (Figure 5), SK-4, is reported (Figure 3) from the Tromsö nappe complex, which correlates with the Niingen nappe complex in Ofoten [*Andresen and Steltenpohl*, 1991, 1994; *Coker*, 1993]. Both hornblende and muscovite cooling ages indicate a general younging toward the south and west, from Late Ordovician-Early Silurian ages in northern Troms to Late Silurian-Early Devonian ages in western Ofoten. The data have been contoured in Figure 7. Contour lines (isochron lines) for hornblende ages are simple and smooth, paralleling the basement-cover contact, clearly documenting younging of the ages toward the west. Muscovite ages also generally young southwestward following the basement-cover contact but a steep gradation of isochron lines corresponds to the base of the Ofoten/Lyngen nappe complexes.

The regional cooling data indicate the following trends. Metamorphism throughout Ofoten-Troms occurred mainly due to the Scandian event, although pre-Scandian relics occur within the outboard terranes of the Upper Allochthon. The two Ordovician hornblende dates from the Tromsö nappe complex (Figure 5) *Dallmeyer and Andresen* [1992], which correlates with the Niingen nappe complex in Ofoten [*Andresen and Steltenpohl*, 1991, 1994], indicate that pre-Scandian relics also occur within the Uppermost Allochthon. Variation in hornblende ages appears to be independent of boundaries between the nappes and shows no simple

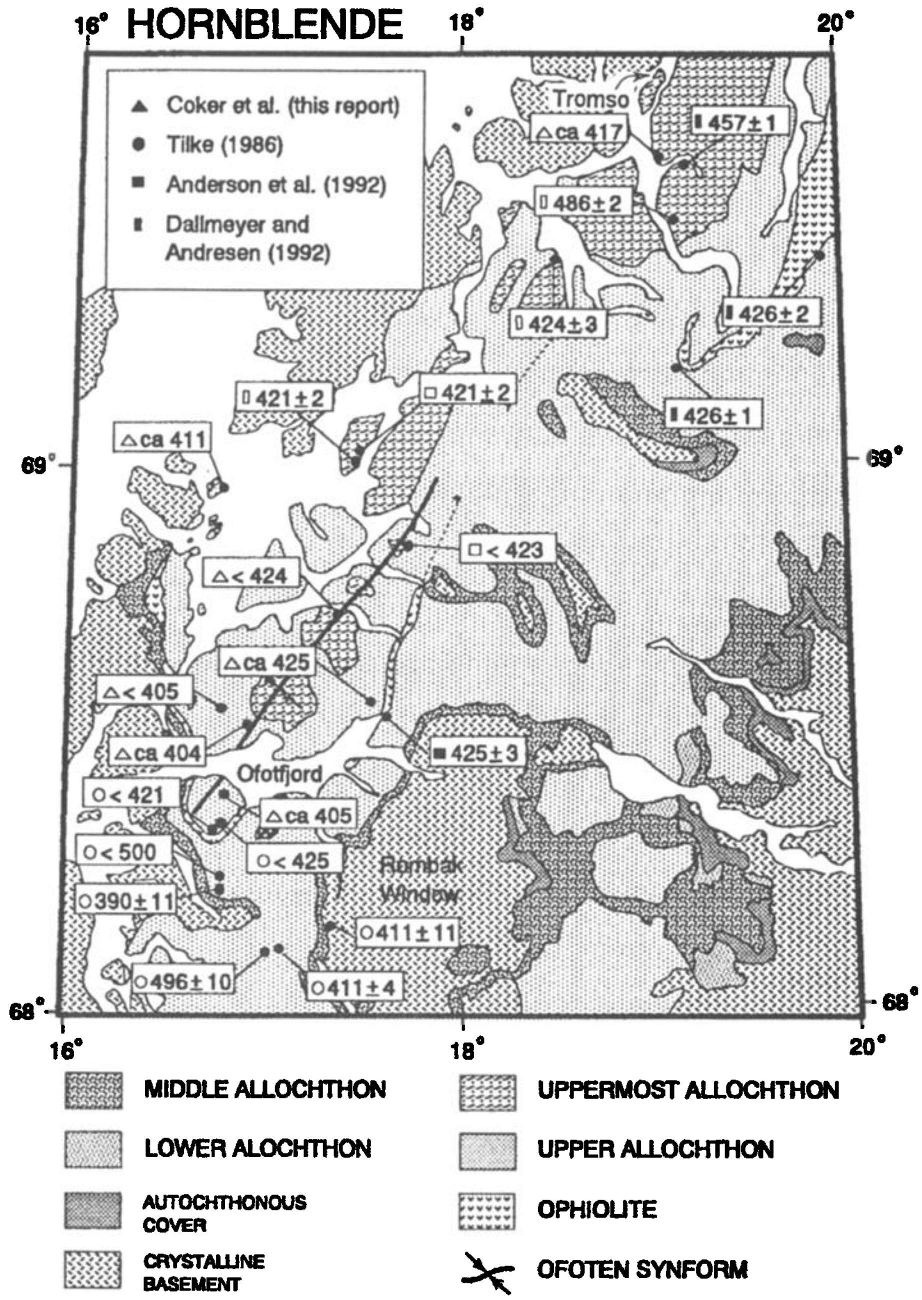

Figure 5. Combined $^{40}Ar/^{39}Ar$ hornblende ages from northern Troms. Data are from *Tilke* [1986], *Dallmeyer and Andresen* [1992], *Anderson et al.* [1992], and this report. Solid symbols indicate plateau dates, and open symbols are correlation dates.

relationship to tectonostratigraphic level (Figure 2), except for the major postmetamorphic fault at the base of the Ofoten/Lyngen nappe complex. The nappes therefore appear to have shared a common cooling history, at least through the 500-350°C temperature interval, consistent with *Steltenpohl and Bartley's* [1987] field and thermobarometric data supporting synmetamorphic thrusting. An important finding is the relatively simple, westward younging hornblende and muscovite cooling patterns which are easiest explained by isostatic adjustment of the footwall of a major west dipping extensional fault. *Norton* [1986], *Séranne and Séguret* [1987], and *Andersen et al.* [1991] each related rapid uplift of deep crustal, Precambrian basement rocks of the Western Gneiss Region of southwest Norway to crustal thinning along a major west dipping normal fault exposed along the west Norwegian coast. *Andersen et al.* [1991] pointed out that uplift of the coesite-eclogite facies Western Gneiss Region "metamorphic core" occurred due to isostatic adjustment of this thinned lithosphere similar to that of metamorphic core complexes of the western U.S. Cordillera.

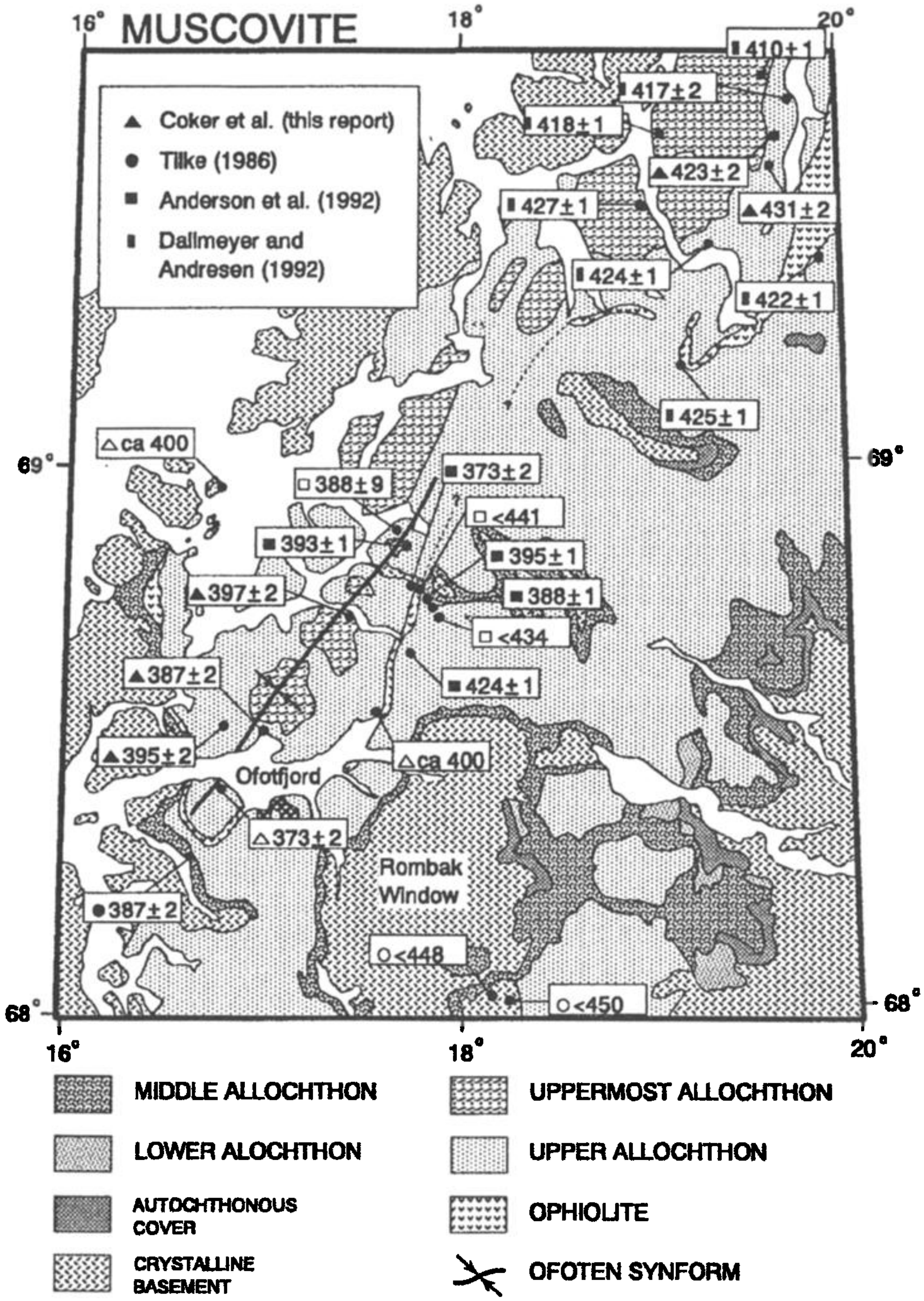

Figure 6. Combined $^{40}Ar/^{39}Ar$ muscovite ages from northern Troms. Data are from *Tilke* [1986], *Dallmeyer and Andresen* [1992], *Anderson et al.* [1992], and this report. Solid symbols indicate plateau dates, and open symbols are correlation dates.

Key evidence for this interpretation is the similarity in ages of (1) footwall block eclogitization of the Baltic continental basement, (2) mineral cooling following this thermal maximum, and (3) deposition of Middle Devonian sedimentary rocks in the hanging wall. *Hames et al.* [1992] reported cooling from a high-pressure, late-Scandian event and subsequent rapid unroofing post-390 Ma, in the Western Gneiss Region of the Lofoten islands directly west of the present study area. The timing reported by *Hames et al.* [1992] is consistent with a continuation into Lofoten of the cooling pattern described herein. Eclogites of uncertain age crop out in the Lofoten islands and, like their southwest Norwegian counterparts, they indicate progressive retrograde development, from eclogite → granulite → amphibolite facies conditions [*Kullerud*, 1992], as is characteristic of the footwall block of metamorphic core complexes [*Wernicke*, 1985]. Although a major west dipping normal fault is not known to be exposed in the Western Gneiss Region west of

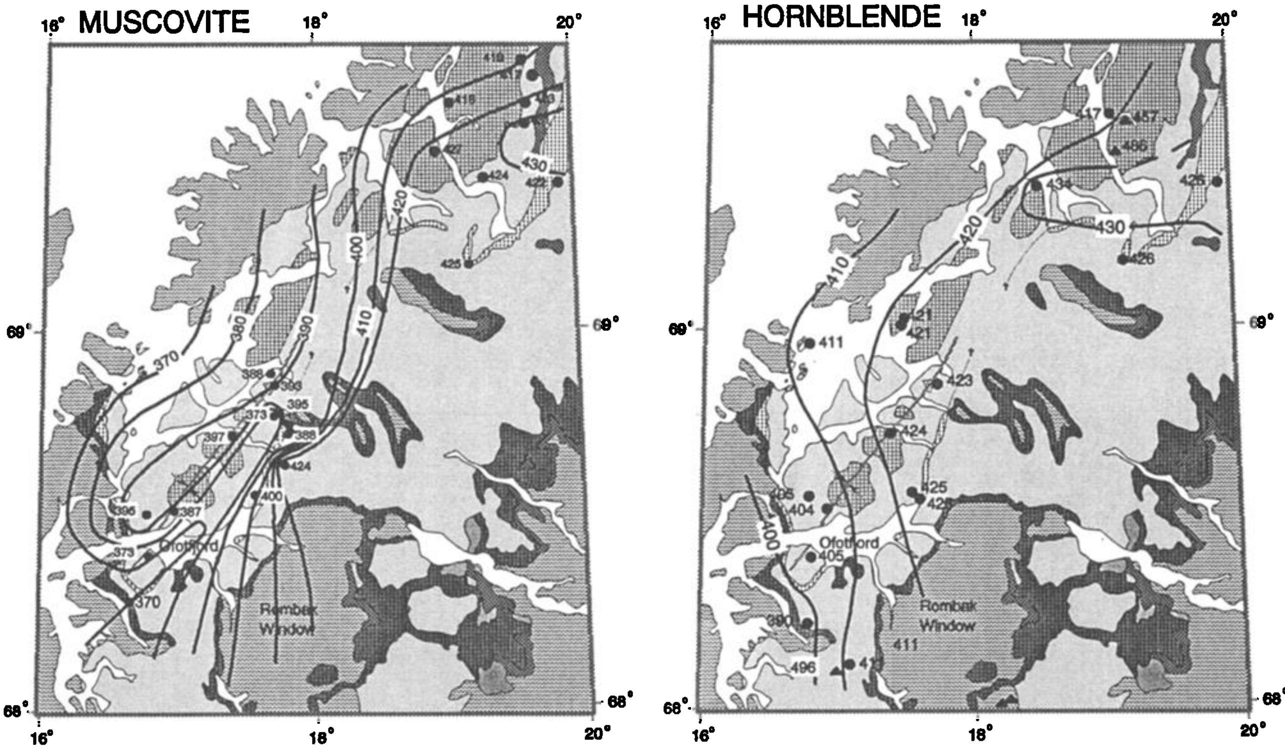

Figure 7. Contoured hornblende and muscovite $^{40}Ar/^{39}Ar$ data from northern Troms. Triangles are pre-Scandian relics. Circles are from the Middle Allochthon.

our study area, it could either be covered by young sediments along the modern continental shelf or have been excised during Cenozoic extension related to the opening of the North Atlantic Ocean. It is possible that several normal faults reactivated previously formed thrust faults, as is common in upper plate rocks of the Caledonian nappe stack in southern Norway [*Fossen*, 1992; *Osmundsen and Andersen*, 1994], to produce the mineral cooling patterns observed for the lower plate Ofoten-Troms rocks. The medium- to low-grade conditions of late-Caledonian metamorphism in rocks of the Ofoten-Troms region is similar to conditions of upper plate rocks in southwest Norway, implying that the amount of section removed during extension in the former area is considerably less. Late-phase, top-to-the-west directed folds and shear zones in western Ofoten that have been difficult to kinematically explain [*Steltenpohl and Bartley*, 1988, 1993; *Rykkelid*, 1992] are compatible with our interpretation.

At apparently the same time that the middle to deep crustal level rocks of the Western Gneiss Region were uplifted, top-to-the-east normal faults also transported rocks toward the foreland. Recent field and U-Pb isotopic work by *Gromet and Andresen* [1993] demonstrates that 395 Ma sphenes, interpreted to date the deformational fabric formed along the Western Gneiss Region basement-cover contact, are younger than reported ages of isotopic systems of similar or lower retentivity in the overlying allochthons. This finding is consistent with the dates compiled and reported herein. *Gromet and Andresen* [1993] argue that the older tectonothermal activity recorded in rocks of the overlying Caledonian allochthons must have been brought down along a top-to-the-east extensional fault onto the deep crustal basement rocks within the lower plate, an interpretation that is at odds with traditional thinking that the Caledonian allochthons were wholly transported along top-to-the-east thrusts. The same authors pointed out geological observations supporting the view that considerable thinning of the crustal section has occurred across the basement-cover contact in this region. A similar interpretation was later reported by *Northrup and Burchfiel* [1993]. We interpret east directed, collapse-driven, normal motion along the east dipping basement-cover contact in western Ofoten to have manifested itself in east directed thrusts toward the foreland. This provides an explanation for the late, out-of-sequence, contractional fault at the base of the Ofoten nappe complex which formed at the same time that the Western Gneiss Region was uplifted. Similarly, *Andersen et al.* [1991] report that the main decompression of the high-pressure rocks of the Western Gneiss Region in south Norway was contemporaneous with the development of the foreland in the southern part of the orogen.

The relation between hinterland uplift/collapse and foreland fold and thrust belt formation is a relatively unexplored topic but most workers attribute foreland structures to tectonic plate convergence. The concept of gravitational spreading of mountain belts, formulated by R. A. Price [*Price*, 1973; *Elliott*, 1976] partly on the basis of the earlier work of Walter Bucher and Hans Ramberg, was largely abandoned because hinterland uplift was considered insufficient to produce the observed upthrusted deformation in the foreland [*Price*, 1981]. Additionally, mountain belts were not at that time known to have stretched and attenuated internal zones. Since the early 1980s, however, high-precision isotopic dating methods have documented rapid and, in some cases, extreme hinterland uplift (for example, exumation of coesite-eclogitized basement in the southwest Norwegian Caledonides [*Andersen et al.*, 1991] and the Hercynides [*Steltenpohl et al.*, 1993]). Following the late 1970s, the application of sense-of-shear criteria to ductile fault zones [*Berthé et al.*, 1979; *Lister and Snoke*, 1984] led to the recognition that many presumed contractional faults in the hinterland actually are extensional structures. Today, the hinterlands of orogenic belts worldwide are known to have a rich and diverse history of extensional movements, as in the western U.S. Cordillera [*Wernicke*, 1985], the Himalayan-Tibetan system [*Burchfiel and Royden*, 1985; *Burchfiel et al.*, 1992], the Alps [*Selverstone*, 1988], the southwest Scandinavian Caledonides [*Andersen et al.*, 1991], the Hercynides [*Steltenpohl et al.*, 1993], the northern [*Getty and Gromet*, 1992] and southern Appalachians [*Maher*, 1987; *Steltenpohl and Kunk*, 1993], and the Laramide belt of the western United States [*Karlstrom and Daniel*, 1993]. In many of these cases, extension in the hinterland is geometrically, kinematically, and temporally linked to foreland-directed contraction. The overall structural, kinematic and temporal plan described herein for the Ofoten region clearly indicates a connection between extension in the hinterland and contraction in the foreland supporting a more universal role for gravitational spreading in the formation of at least this part of the Caledonides.

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