Journal of the Geological Society, *London*, Vol. **155,** 1998, pp. 297–309. Printed in Great Britain.

The tectonic significance of pre-Scandian $^{40}Ar/^{39}Ar$ phengite cooling ages in the Caledonides of western Norway

TORGEIR B. ANDERSEN[1], HENRY N. BERRY IV[2], DANIEL R. LUX[3] & ARILD ANDRESEN[1]

[1]*Institutt for Geologi, Universitetet i Oslo, PO Box 1047, 0316 Blindern, Oslo, Norway*
(e-mail: t.b.andersen@geologi.uio.no)
[2]*Maine Geological Survey, 22 State House Station, Augusta, ME 04333, USA*
[3]*Department of Geological Sciences, 119 Boardman Hall, University of Maine, Orono, ME 04469, USA*

Abstract: Pre-Silurian continental-margin deposits in western Norway, non-conformably overlying allochthonous continental orthogneisses retain Ordovician $^{40}Ar/^{39}Ar$ cooling ages for phengites, implying either rapid cooling immediately after a Late Ordovician orogenic event, or less likely, a slow cooling following an Early Ordovician or older orogeny. The Dalsfjord Suite–Høyvik Group basement–cover pair are probably a lateral equivalent to Late Proterozoic sandstones ('sparagmites') covering the Jotun Nappe gneisses of the Middle Allochthon in central-south Norway. The Høyvik Group underwent polyphase deformation, greenschist-facies metamorphism (T_{max} <450°C) and exhumation prior to deposition of the unconformably overlying Wenlockian continental-margin deposits of the Herland Group. The Høyvik Group was only weakly metamorphosed during obduction of the Solund–Stavfjord Ophiolite and the Scandian continental collision between Baltica and Laurentia. Phengitic white micas from the Høyvik Group yield cooling ages of 446.1 ± 3.0, 449.1 ± 2.2 and 447.5 ± 4.0 Ma, respectively, identical within experimental error. One sample gives a plateau over 72% of the gas analysed, whereas the other samples were slightly disturbed after initial cooling, as indicated by systematically lower apparent ages at low experimental extraction temperatures. Minor ^{40}Ar loss probably occurred during subsequent Scandian deformation and late to post-orogenic extension.

The Høyvik Group rocks were unroofed before the Wenlock time (423–428 Ma) and cooled through the temperature for argon retention in phengite at *c.* 447 ± 4 Ma, indicating a maximum cooling rate between 14 and 22°C/Ma^{-1} through Ashgill and Llandovery times before being subjected to low-grade metamorphism during the Scandian orogeny. Rapid pre-Scandian cooling, combined with peak metamorphic conditions of 450°C or less, may indicate that the Dalsfjord–Høyvik basement–cover pair were affected by an orogenic event during the Late Ordovician (Caradoc) time. The data also suggest that the Caledonian margin of Baltica may have experienced a more protracted tectonism during the Caledonian cycle than previously models focusing on Early Caledonian and Tremadoc (or older) ophiolite obduction and the Scandian continental collision between Baltica and Laurentia.

Keywords: Caledonides, Norway, Upper Proterozoic, phengite, $^{40}Ar/^{39}Ar$.

The Scandinavian Caledonides are dominated by Scandian deformation and metamorphism caused by the Silurian–Devonian continental collision between Baltica and Laurentia. Although older features are incompletely preserved at best, a polyphase tectonic evolution is convincingly documented by several occurrences of pre-Scandian unconformities from south to north along the Scandinavian Caledonides (Sturt *et al.* 1985). Inspired by models from Finnmark in northern Norway (Sturt *et al.* 1978), most tectonic reconstructions of the Scandinavian Caledonides infer that the Baltic miogeocline (Fig. 1) was affected by Cambrian–Early Ordovician deformation and metamorphism broadly known as the Finnmarkian phase. At issue is whether tectonic events between Early Ordovician and Late Silurian time may have significantly affected the Baltic margin, or whether events in that time interval were restricted to outboard terranes in the oceanic realm. Extensive tracts of the former Baltic margin and outboard terranes are now preserved in Scandian allochthons that were thrust eastward onto the Baltic craton and then partially dismembered by late-orogenic extensional collapse (Roberts & Gee 1985).

The complexity of the pre-Scandian tectonic history in the accreted oceanic terranes of the Upper Allochthon (Fig. 1) is well documented by unconformities such as in the Hardanger–Sunnhordland Region in western Norway (Andersen & Andresen 1994). These unconformities, however, and are not necessarily related to tectonism also affecting the Baltic margin. Eclogites in allochthonous continental rock of the Lindås Nappe of the Bergen area (Austrheim 1987) apparently have a pre-Scandian origin, as indicated by $^{40}Ar/^{39}Ar$-cooling ages of *c.* 450 and 430 Ma from amphibole and muscovite, respectively (Boundy *et al.* 1996). But again, the relationship of the Lindås Nappe to Baltica at that time is suspect and yields no conclusive evidence for the pre-Scandian orogenic involvement of the Baltic margin.

Mapping in the Otta and Foldal areas of central-south Norway provides evidence for pre-Scandian ophiolite obduction onto rocks considered to be of Baltic affinity (Sturt & Roberts 1991; Sturt *et al.* 1991, 1995; Bøe *et al.* 1993; Bjerkgård & Bjørlykke 1994). This event occurred during or before the Early Ordovician. Parts of the former Baltic margin preserved in the Seve Nappes of northern Sweden (Svenningsen 1993), contain eclogites and associated rocks that have given Late Cambrian to Early Ordovician isotopic ages (Mørk *et al.* 1988; Dallmeyer *et al.* 1991). These lines of structural, metamorphic and isotopic evidence have been taken

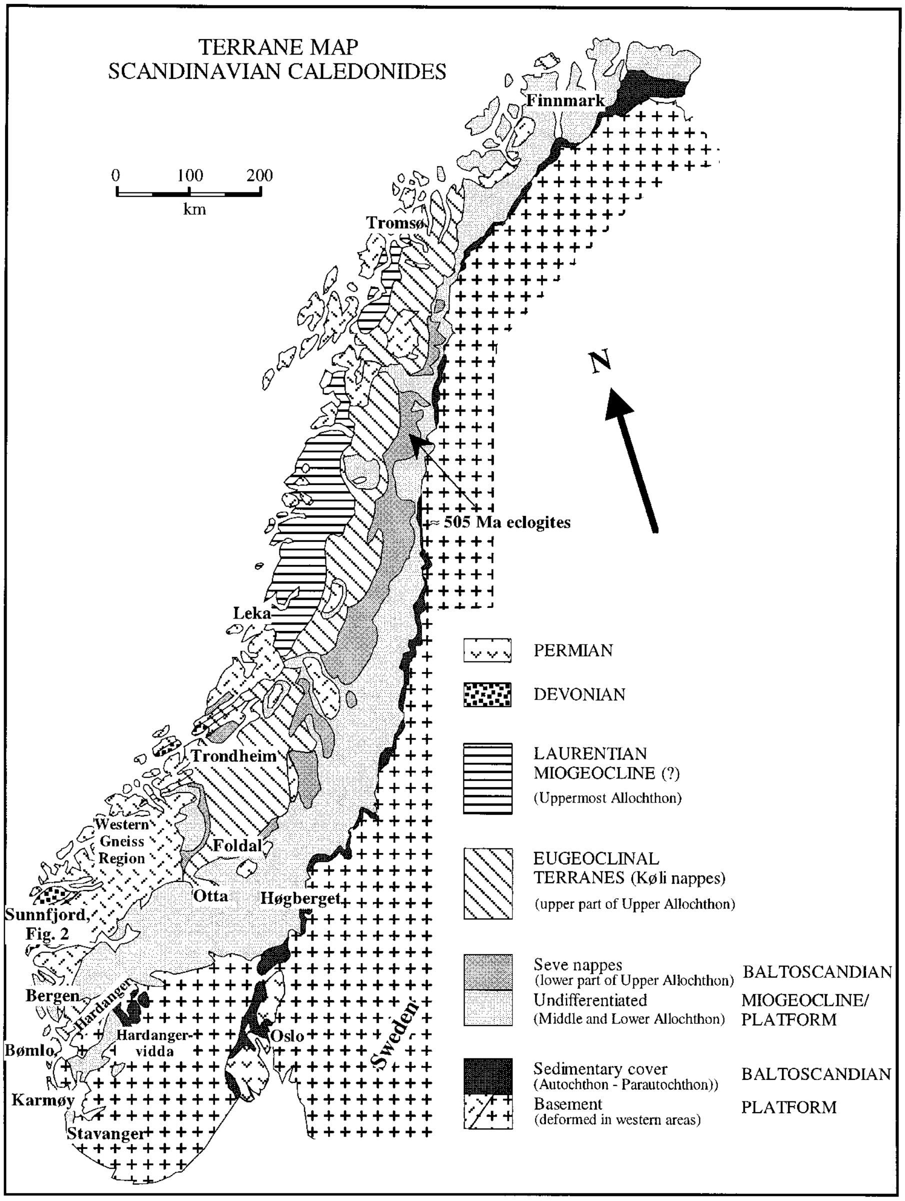

Fig. 1. Simplified tectonic map of the Scandinavian Caledonides highlighting the distribution of tectonostratigraphic terranes of Baltic and outboard affinity. Location of Fig. 2 and areas discussed in the text are shown.

together to indicate subduction of the Caledonian margin of Baltica in Mid to Late Cambrian time, followed by Early Ordovician uplift and cooling (Andréasson 1994). Due to the paucity of well-preserved fossils in critical localities, these interpretations have to a large extent been based on dating of events by isotopic techniques without the added benefit of stratigraphic age control (see review by Andréasson 1994).

In 1984, a spectacularly preserved unconformity between fossiliferous Silurian rocks of the Herland Group and previously deformed and metamorphosed continental margin meta-sediments of the Høyvik Group (Fig. 2) was discovered on Atløy in western Norway (Brekke & Solberg 1987). The significance of the sub-Herland Group unconformity to the tectonic evolution of the Caledonian margin of Baltica was regarded as uncertain because of the allochthonous, hence suspect, status of the rocks on Atløy (Andersen & Andresen 1994). The Høyvik Group is now, however, considered as Late Proterozoic miogeoclinal sedimentary cover deposited on basement of Baltic affinity. If the latter correlation is correct, then the sub-Herland Group unconformity records a pre-Scandian tectonometamorphic event that occurred on the Baltic margin.

The age of the pre-Scandian tectonism that affected the Høyvik Group has, until the present study, been constrained only to be older than the Wenlock age of the unconformably overlying Herland Group. The purpose of this study is to more tightly constrain the age of the pre-Scandian event by dating white micas that define the pre-Scandian foliation in low grade schists of the Høyvik Group. The combination of stratigraphic age control and minimal Scandian disturbance makes this a rare opportunity to evaluate the age of pre-Scandian deformation on the Baltic margin. The isotopic data from the Atløy area in western Norway, in combination with other pre-Scandian age data from the region, add to the understanding of the tectonic evolution of the Scandinavian Caledonides. The ^{40}Ar/^{39}Ar ages reported here from the Høyvik Group are part of a major Ar-dating project (131 Ar mineral spectra from 64 samples) involving rocks from the lower, middle, and upper crustal rocks in western Norway (Berry *et al.* 1993, 1994).

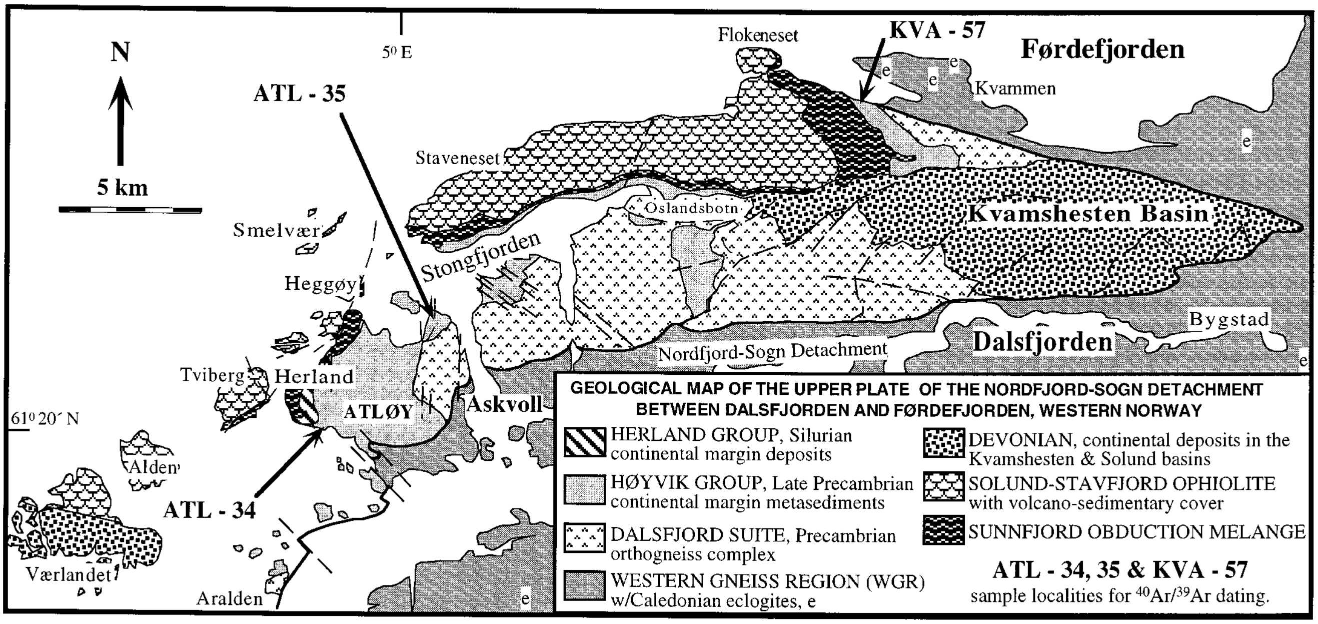

Fig. 2. Geology of the upper plate of the Nordfjord–Sogn Detachment between Førde and Dalsfjorden in western Norway. Note location of samples used in the ^{40}Ar/^{39}Ar investigation.

Geological setting

The rocks dated in this study are structurally positioned in the hanging wall of the extensional Nordfjord–Sogn Detachment. The Detachment footwall constitutes the eclogite-bearing metamorphic core complex of the Western Gneiss Region, rapidly decompressed by processes related to late and post-orogenic extension (Norton 1986; Séranne & Séguret 1987; Andersen & Jamtveit 1990; Andersen *et al.* 1994). The present fault contact between the foot- and hanging walls of the Nordfjord–Sogn Detachment was reactivated by Permian, Jurassic and younger undated movements (Torsvik *et al.* 1992; Eide *et al.* 1997). The hanging wall of the Nordfjord–Sogn Detachment preserves a complicated structure related to pre-Scandian and Scandian mountain building, as well as the late to post-Caledonian extensional events. The Caledonian rocks and structures in the hanging wall of the Nordfjord–Sogn Detachment are unconformably overlain by Devonian continental deposits (Osmundsen 1996).

The tectono-stratigraphy of the upper plate of the Nordfjord–Sogn Detachment in the Sunnfjord area is shown schematically in Fig. 3 (modified from Osmundsen 1996). The Dalsfjord Suite comprises mangeritic gneisses associated with subordinate anorthosite and variably deformed granitic and gabbroic rocks of probable Middle Proterozoic age (Kolderup 1921; Brekke & Solberg 1987; Andersen *et al.* 1990). The Dalsfjord Suite is non-conformably overlain by the psammite-dominated Høyvik Group with a maximum structural thickness in the study area in the order of 1.5 to 2 km (Andersen & Dæhlin 1986; Brekke & Solberg 1987). The Høyvik Group was intruded by pre-orogenic mafic dykes compositionally similar to the dykes of the Särv Nappe of the central-east Scandinavian Caledonides (Dæhlin & Andersen 1988). The mafic rocks are variably preserved as meta-dolerites, locally with pseudomorphic magmatic textures, but in most localities they are greenstones/greenschists with secondary texture and mineralogy. Meta-basalts with poorly preserved pillow structures and a MORB-type geochemistry similar to the dykes, are present near the uppermost preserved stratigraphic levels of the Høyvik Group (Andersen *et al.* 1990). The Høyvik Group and the associated dykes probably correlate with the Late Proterozoic psammite-dominated meta-sedimentary rocks and dykes in the Seve Nappes and in the rocks of the Middle Allochthon interpreted to represent the stacked Caledonian miogeocline of Baltica (Andréasson 1994; Svenningsen 1993). The rocks of the Dalsfjord–Høyvik basement–cover pair underwent pre-Silurian deformation and metamorphism. The meta-sediments and the associated greenstones have typical greenschist-facies assemblages. The greenstones have albite–chlorite–epidote–actinolite assemblages. Garnet, controlled by bulk composition is very locally present in pelitic rocks on northern Atløy (Fig. 2), but other metamorphic index minerals have not been observed in the generally quartz-rich, biotite–muscovite mica schists and psammites. The metamorphism for the pre-Scandian event recorded in the rocks between Dalsfjorden and Førdefjorden thus represents a typical biotite zone in a Barrovian zonal scheme.

The Silurian Herland Group rests with a remarkably well-preserved unconformity (Fig. 3) upon the Høyvik Group rocks (Brekke & Solberg 1987). Fossils in the Herland Group are of Wenlock age (M. Johnson pers. comm. 1989; D. Harper pers comm. 1994). The Scandian deformation in the Atløy area is unusually weak compared to most areas in western Norway. The deformation of the Herland Group and the stratigraphically overlying Sunnfjord Melange formed during obduction of the Solund–Stavfjord Ophiolite Complex was described by Andersen *et al.* (1990). Zircons from a diorite within the ophiolite have a U–Pb age of 443 ± 3 Ma (Dunning & Pedersen 1988) corresponding to an Ashgill–Llandovery age of formation. The Solund–Stavfjord Ophiolite Complex is overlain by the Stavenes Group, dominated by meta-greywackes with abundant shallow intrusive and volcanic rocks of MORB affinity (Furnes *et al.* 1990). Because the obduction of the ophiolite is reflected in the stratigraphy of the Silurian rocks of the Herland Group (Andersen *et al.* 1990), the emplacement onto the continental

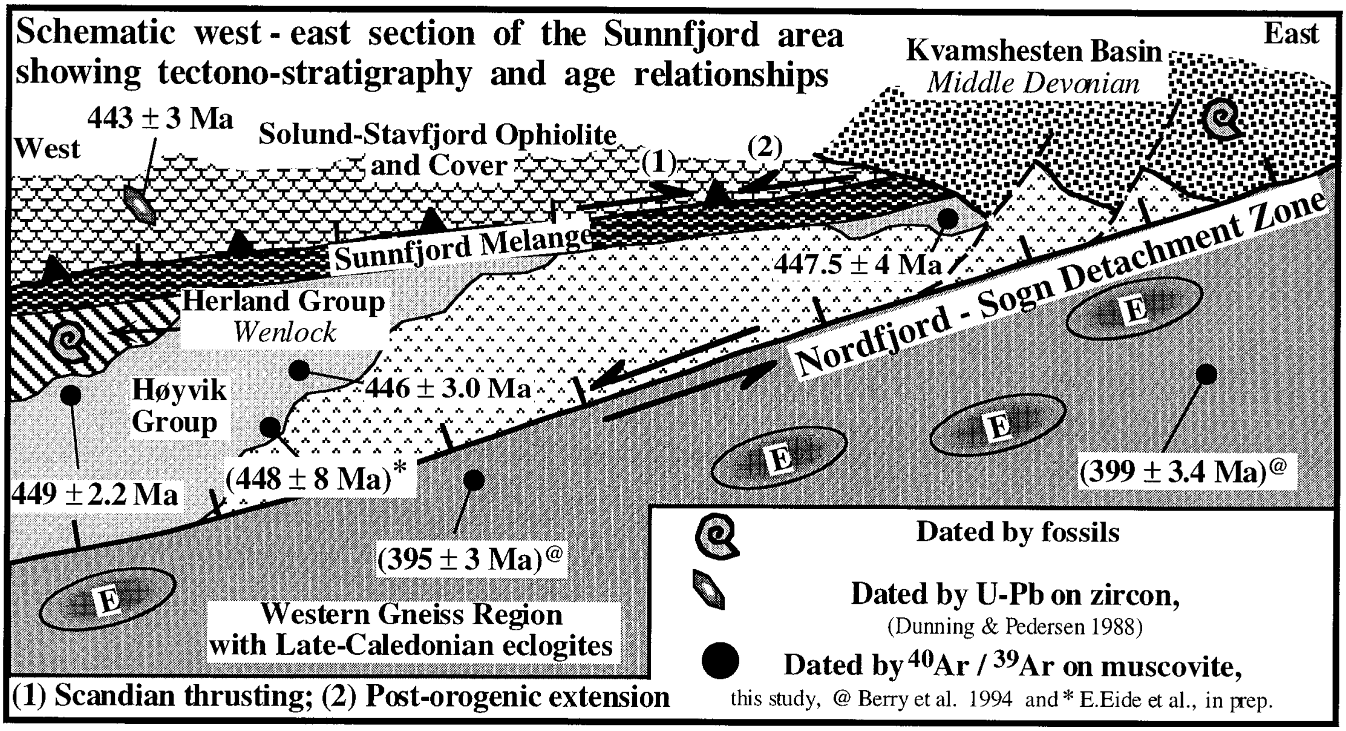

Fig. 3. Schematic west–east cross-section showing simplified age relationships and tectonostratigraphy of the Sunnfjord Region. Positions of the samples dated in this study, by Berry *et al.* (1994) and by Eide *et al.* (1997) are shown.

margin can be relatively accurately timed to the Wenlock (428–423 Ma).

Structures related to the building of the Caledonian orogen are well preserved in the hanging wall of the Nordfjord–Sogn Detachment. These include the pre-Scandian structures in the Dalsfjord–Høyvik basement–cover pair, as well as structures related to Scandian deformation (Andersen *et al.* 1990; Osmundsen & Andersen 1994; Osmundsen 1996). From the cross-cutting relationships along the unconformity of the Herland Group it can be demonstrated that the main fabrics of the Høyvik Group in the Atløy area are older than the Silurian rocks. The pre-Scandian main foliation is folded by open to tight folds with associated crenulation cleavages, which in turn are truncated by the unconformity, thus demonstrating the polyphase nature of the pre-Silurian deformation. The Scandian and extension-related structures in Høyvik Group on Atløy, are dominated by open large-scale folds and flexures and extensional shear zones and faults occurring mainly in the northwestern part of the island (Andersen *et al.* 1990; Osmundsen & Andersen 1994; Osmundsen 1996).

The uppermost stratigraphic level preserved in the hanging wall of the Nordfjord–Sogn Detachment is represented by the unconformable Devonian continental deposits, in Sunnfjord expressed by the Kvamshesten basin (Osmundsen 1996). The Devonian sediments rest unconformably upon the tectono-stratigraphy described above, but are in faulted contact with rocks of the lower plate along the Nordfjord–Sogn Detachment (Fig. 3).

Sampling strategy

For the present investigation we have sampled the Høyvik Group from two structural settings. The first setting, comprising two localities, has minimal structural overprint from Scandian contractional and post-orogenic extensional structures. ATL-35 (UTM 862120) was collected within the Høyvik Group on northern Atløy, approximately 1.5 km structurally below the Silurian unconformity (Figs 2 and 3). ATL-34 (UTM 824070), was collected closer to the stratigraphic base of the Herland Group on southwest Atløy, approximately 500 m below the unconformity. Outcrop-scale structural features related to Scandian deformation were not identified at these localities, and we are confident that the white micas analysed from ATL-34 and ATL-35 crystallized during development of the main pre-Scandian foliation.

Our second sampling target, KVA-57 (UTM 045199), is from a meta-sandstone from the Høyvik Group in a structural setting approximately 200 m below a major Scandian thrust near Kvammen on the mainland east-northeast of Atløy (Fig. 2). Because of structural conformity between the Høyvik Group and the Sunnfjord Melange lithologies, the Silurian unconformity cannot be easily identified in this area; the relative age of the main fabric in the Høyvik Group sandstones in the field cannot be separated with certainty from those of the Sunnfjord Melange. The shear zone above the sampled locality puts the Solund–Stavfjord Ophiolite Complex structurally above the Sunnfjord Melange and over the Dalsfjord–Høyvik basement–cover pair and is clearly a major Scandian structure (Fig. 3). The Herland Group lithologies have not been recognised in the structural section in this area.

Disharmonic folds and kink folds which post-date the main foliation in the Høyvik Group are interpreted to have formed during the Scandian deformation. Phyllonitic mica-schists in the overlying Sunnfjord Melange lithologies show strong Scandian as well as Post-Scandian extensional fabrics. The thrust zone was reactivated as a normal shear zone during extension as shown by common top-west, normal-slip crenulation cleavages (Osmundsen 1996). Furthermore, the KVA-57 locality is structurally positioned near base of the hanging wall of the Nordfjord–Sogn Detachment (Fig. 3). This zone is commonly affected by brecciation and fluid infiltration related to repeated reactivation of the detachment.

Description of analysed samples

Petrography

All three samples of thinly bedded metamorphosed feldspathic sandstones contain 75–85% quartz, 8–15% feldspar, and 5–15% white mica (phengite), with <5% other minerals. A metamorphic foliation is defined by alignment of the mica as individual plates or in thin folia within the psammites. The foliation is anastomosing, and kinematic indicators are neutral or give opposing shear senses within a thin section so the foliation is interpreted as an axial planar fabric associated with common isoclinal folds such as those overlain unconformably by the Herland Group. Late Caledonian extension and Permian to Jurassic reactivation produced widespread brittle faults and fractures above the Nordfjord–Sogn Detachment (Torsvik *et al.* 1992; Osmundsen 1996; Eide *et al.* 1997). While major fractures were avoided in sampling, microscopic fractures are present in the three analysed samples and are most common in sample ATL-34.

Micro-structural characteristics of the foliation are similar for the three samples. Quartz shows undulatory or patchy extinction. Some of the larger grains contain deformation bands. Quartz–quartz grain boundaries are sutured and exhibit extensive subgrain development. Some microcline grains have weakly undulate extinction, particularly in the outer parts of large grains, whereas plagioclase and most microcline grains show uniform extinction and only brittle deformation. Feldspar grain boundaries are sharp and smoothly curved. The biotite zone mineral assemblages as well as the quartz and feldspar micro-structures suggest that deformation occurred at temperatures of less than 450°C, and that no significant mineral growth occurred after the main deformation.

Most grains of phengite are bent or gently kinked, although some show uniform extinction and are apparently undeformed. The deformed grains are not affected throughout, but have larger undeformed areas separated by narrow deformed zones. Cleavage and extinction position curve smoothly through the deformed zone, indicating that a ductile dislocation mechanism rather than cataclastic deformation has affected these grains. Post-deformational recovery of the crystal structure is inferred to be small, because strained grains have not recrystallised into smaller, polygonal grains. In all three samples the micas which define the foliation are deformed in the manner just described. In sample KVA-57, some of the micas are deformed further by microscopic crenulations associated with the younger outcrop-scale folds. Some of the micas in sample ATL-34 are deformed by late, cataclastic microbreccia zones, but these late deformation zones are thin and affect only a small volume proportion of the mica in the rock.

White mica chemistry

Grain mounts were prepared of the 'white' micas, which actually have a pale olive-green colour. Four or five grains from each sample were analysed by electron microprobe to determine the compositional variations within the sample and to allow comparison among the three samples. Analyses were done by A. V. McGuire at the Texas Centre for Superconductivity, University of Houston on a JEOL 8600 Superprobe. Natural and synthetic mineral standards were used. Analytical conditions were 15 kV accelerating voltage, 20 nA beam current, 40 s count time (20 s on Na), with the beam defocused.

The variability within each sample is small (Fig. 4). Both the petrography and the chemical analyses indicate only one episode of mica growth in an individual sample, so it is valid to average the analyses of several grains from each sample (Table 1). In all three samples the white mica is phengitic. The amount by which Si exceeds the 6.0 cations of ideal muscovite (per 22 oxygens) is approximately equal to the octahedral Mg, suggesting a Tschermak ($Mg+Si \rightarrow Al+Al$) substitution. Although the iron oxidation state can not be determined from microprobe analyses, all Fe is reported as Fe_2O_3 in Table 1. Several reasons suggest that most or all the iron is ferric, (1) all samples contain hematite, which indicates a high oxidation state; (2) magnesium alone provides enough divalent cations to compensate for the excess Si by a Tschermak substitution with no ferrous iron required; (3) assuming ferric rather than ferrous iron, the calculated number of octahedral cations is closer to four and the calculated weight percent totals are closer to 100. Some authors have referred to phengites with such large ferric iron contents as ferriphengites (Guidotti 1984).

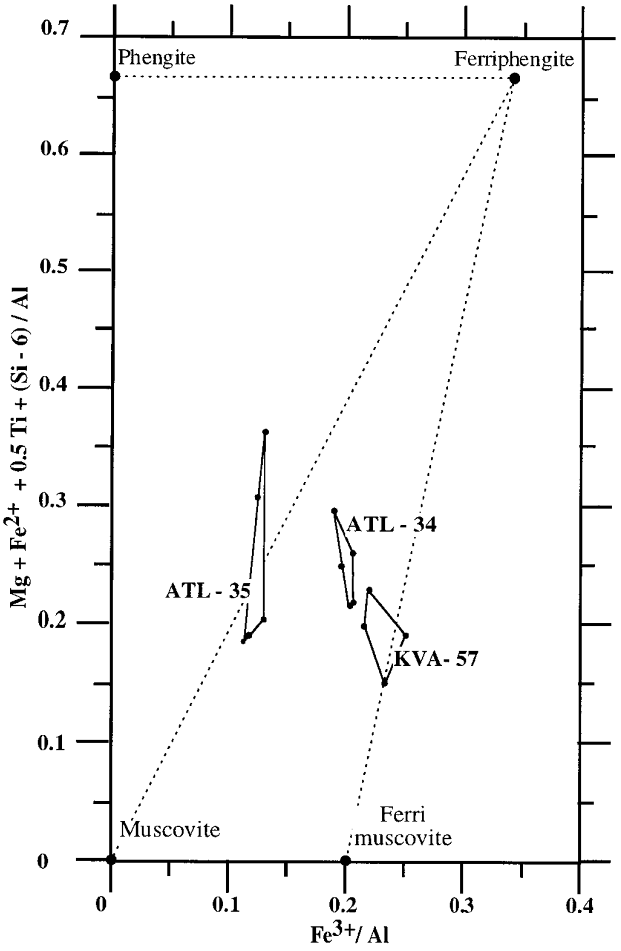

Fig. 4. Plot showing composition of ferriphengites from the Høyvik Group. Dots indicate individual microprobe analyses from grain mounts of mineral concentrates.

The phengites from samples ATL-34 and KVA-57, which contain microcline and plagioclase, have the highest amount of ferric iron and the lowest octahedral aluminum. Micas from ATL-35, in which plagioclase is the only feldspar, have significantly less ferric iron and more aluminum (Table 1). This systematic relationship between mica composition and feldspar assemblage is the expected effect of rock bulk composition on mica crystal chemistry (Guidotti 1969). We can thus conclude that the phengites approached chemical equilibrium with the other phases in each rock during metamorphism, and it is unlikely that they could be detrital grains.

Geochronology

Analytical methods

Whole rock samples were disaggregated by crushing. Phengites from the 100–150 μm size fraction were concentrated by standard mineral separation techniques to an estimated purity of 99.5% or greater. The principal impurities consist of small inclusions of quartz, opaque minerals, or chlorite. At the final stage, the phengite concentrates were washed in an ultrasonic cleaner and sieved again to reduce the number of polycrystalline grain aggregates. Between 120 and 140 mg of phengite from each sample were encapsulated in Sn foil and irradiated in the L67 position of the Ford Nuclear Reactor at the University of Michigan. An intralaboratory muscovite standard of known age, SBG-7 (=240.9 Ma relative to MMhb-1 of Alexander *et al.* 1978), was irradiated with the unknowns to monitor the neutron flux.

Table 1. *Composition of pherriphengites from the Høyvik Group, western Norway*

Sample number	ATL-34	ATL-35	ATL-57
No. of points analyzed	4	5	4
Wt % oxide			
SiO_2	47.20	48.05	46.16
TiO_2	1.08	0.95	1.00
Al_2O_3	29.97	28.61	26.70
Fe_2O_3*	8.87	5.32	9.90
MnO	0.01	0.02	0.02
MgO	2.63	3.09	2.20
CaO	0.00	0.00	0.00
Na_2O	0.08	0.11	0.06
K_2O	7.87	7.63	8.12
BaO	0.16	0.40	0.21
ZnO	0.03	0.03	0.01
F	0.00	0.05	0.05
Cl	0.00	0.00	0.04
Analysed total	93.90	94.26	94.47
O equiv. F, Cl	0.00	−0.02	−0.03
Ideal H_2O†	4.39	4.44	4.35
Recalc. total	98.29	98.68	98.79
Structural formulas based on 22 oxygens			
Si	6.45	6.45	6.31
Al	1.55	1.55	1.69
Total^{IV}	8.00	8.00	8.00
Al	2.63	2.98	2.62
Ti	0.11	0.10	0.10
Fe 3+	0.91	0.54	1.01
Mn	0.00	0.00	0.00
Mg	0.54	0.62	0.45
Zn	0.00	0.00	0.00
Total^{VI}	4.19	4.23	4.19
Ca	0.00	0.00	0.00
Na	0.02	0.03	0.02
K	1.37	1.31	1.42
Ba	0.01	0.02	0.01
Total XII	1.40	1.36	1.44
F	0.00	0.02	0.02
Cl	0.00	0.00	0.01
OH†	4.00	3.98	3.97
Total anion	4.00	4.00	4.00

*All Fe reported as Fe_2O_3

†Assumes 4 anions per 22 oxygens.

The reported compositions are averages of four or five analyses as indicated in text.

K and Ca salts were also irradiated to monitor the generation of interfering isotopes and to calculate appropriate correction factors (after Dalrymple *et al.* 1981).

The samples were analysed at the University of Maine by the $^{40}Ar/^{39}Ar$ step heating technique (Merrihue & Turner 1966; McDougall & Harrison 1988). Samples were heated in a Mo crucible with a radiofrequency generator. This system provides precise relative temperature control during an incremental heating experiment, but the nominal temperature scale reported for a given sample has an uncertainty estimated at ± 50°C. The isotopic composition of Ar was measured using a Nuclide 6-60-SGA 1.25 mass spectrometer. Gas purification and the derivation of values reported in Table 2 from measured values follow procedures described by West *et al.* (1992).

Apparent ages were calculated using decay constants and isotope abundances recommended by Steiger & Jäger (1977) and equations of Dalrymple *et al.* (1981). Total gas ages are sample averages weighted according to increment size. Plateau ages are obtained by averaging the apparent ages of contiguous increments whose ages overlap at the 95% confidence level as defined by the critical value test (Dalrymple & Lanphere 1969). Plateau uncertainties are reported at the 2σ level. All comparisons of absolute ages to the geological time scale used in this paper follow the calibration of Tucker & McKerrow (1995).

Results

Total gas ages for the three samples are 445.8 ± 4.0, 444.4 ± 4.1, and 440.0 ± 4.0 Ma for ATL-34, ATL-35 and KVA-57, respectively (Table 2). While the total gas ages are similar, the difference between the youngest and the oldest ages exceeds the critical value of 5.54 Ma and demonstrates with 95% confidence that their total gas ages are different. The incremental age spectra are also generally similar, although not identical (Fig. 5). In all cases the initial increment gives the youngest age and apparent ages increase of the first 10–20% gas released to approach the total gas ages.

Sample ATL-35 gives a plateau age of 446.1 ± 3.0 Ma for 72% of the gas released. Apparent ages for the other two samples gradually but steadily increase to a maximum apparent age at the highest extraction temperature. While they do not give plateaux for significant amounts of gas released, the discordances are not large. For sample ATL-34, apparent ages for 90% of the gas range over only 5.9 Ma; for KVA-57, apparent ages for 89% of the gas range over 11.1 Ma, less than 3% of the total gas age. The final two increments of ATL-34, which constitute 26% of the gas, overlap with an age of 449.1 ± 2.2 Ma. The maximum reliable age for KVA-57 is 447.5 ± 4.0 Ma.

All three age spectra are superimposed in Fig. 5b, to allow ‘an aid to the eye’ comparison. The overlap of the discordant increments in the first 15% of gas released strongly suggests that the initial low apparent ages are characteristic of the suite of samples. Over the interval from 15 to 40% of gas released, sample KVA-57 gives apparent ages slightly, yet distinctly, younger than ATL-34 and ATL-35. For the final 60% of gas released, the apparent ages for all three overlap within uncertainties. The ‘best estimate’ of cooling ages for samples ATL-34 and KVA-57 are thus minima for the timing of their cooling through their phengite blocking temperatures.

Interpretation

The plateau for sample ATL-35 indicates a homogeneous argon isotopic content and implies that the phengite was essentially closed to argon diffusion after cooling. We interpret the plateau age of 446.1 ± 3.0 Ma to give the time at which the sample cooled through the phengite Ar-retention temperature.

Discordant $^{40}Ar/^{39}Ar$ release spectra such as those obtained from ATL-34 and KVA-57 (Fig. 5) indicate a heterogeneity in argon isotopic composition within the sample. Theoretical and empirical studies have shown that such spectra may reflect either slow cooling of a sample with a range of grain sizes (Dodson 1973; Villa & Zeitler 1988); partial argon loss by volume diffusion during a thermal event subsequent to cooling (Turner 1968); or partial argon loss by deformation of grains subsequent to cooling (Costa & Maluski 1988; Hames & Hodges 1993). Apparent age gradients which might result from analysing a mixture of grains which grew at different times (Lanphere & Albee 1974; Ross & Sharp 1988; West & Lux

Table 2. *^{40}Ar/^{39}Ar data from phengites from the Høyvik Group, hanging wall of the Nordfjord–Sogn Detachment, Sunnfjord*

Temp (°C)	^{40}Ar/^{39}Ar	^{37}Ar/^{39}Ar ($\times 10^{-4}$)	^{36}Ar/^{39}Ar ($\times 10^{-4}$)	^{39}Ar (% of total)	^{40}Ar (%)	Apparent age (Ma)
ATL-34 Phengite, sample weight = 137.5 mg, J = 0.015927						
575	17.44	53.2	56.946	0.9	90.2	403.5 ± 4.7
700	17.13	16.1	8.303	2.9	98.5	429.3 ± 0.3
800	17.41	6.8	0.308	6.1	99.8	440.9 ± 0.3
850	17.51	8.7	0.088	7.3	99.9	443.3 ± 0.4
900	17.58	10.3	0.775	7.1	99.8	444.3 ± 0.8
950	17.60	12.8	1.177	7.1	99.7	444.5 ± 0.6
1000	17.66	3.4	0.063	8.7	99.9	446.7 ± 0.2
1060	17.68	10.4	0.245	9.5	99.8	447.0 ± 0.4
1110	17.70	12.3	0.0558	8.8	99.9	447.5 ± 0.2
1160	17.72	16.1	1.163	7.7	99.7	447.3 ± 0.7
1200	17.73	10.9	0.026	7.9	99.9	448.3 ± 0.4
1270	17.77	9.0	0.062	12.3	99.0	449.2 ± 0.2
Fuse	17.81	17.81	24.7	13.6	99.6	449.1 ± 0.3
Total gas age				100.0		445.8 ± 4.0
Plateau age (increment 1270 and fuse)						449.1 ± 2.2
ATL-35 Phengite, sample weight = 120.7 mg, J = 0.010879						
500	29.12	235.1	202.457	1.4	79.4	404.8 ± 2.1
700	25.96	59.9	40.329	2.8	95.4	430.2 ± 1.2
800	25.46	86.5	14.893	3.1	98.2	434.1 ± 4.0
880	25.61	233.8	8.735	5.5	98.9	439.3 ± 0.9
950	25.82	58.0	0.768	12.9	99.9	446.0 ± 0.4
1000	25.86	31.3	1.709	11.6	99.7	446.2 ± 0.5
1060	25.89	47.9	1.986	9.7	99.7	446.5 ± 0.4
1110	25.92	30.8	3.575	13.0	99.5	446.3 ± 0.7
1180	25.83	30.7	1.255	12.7	99.8	446.0 ± 0.5
1240	25.85	67.8	2.424	12.5	99.7	445.8 ± 1.0
1320	25.83	46.7	2.187	10.8	99.7	445.5 ± 0.5
Fuse	26.13	74.9	5.197	3.9	99.4	448.8 ± 2.0
Total gas age				100.0		444.4 ± 4.1
Plateau age (increments 950 through 1240)				74.4		446.1 ± 3.0
KVA-57 Phengite, sample weight = 140.3 mg, J = 0.015894						
459	19.17	16.6	146.517	0.6	77.3	381.5 ± 6.0
700	16.92	20.0	12.649	3.7	97.7	420.8 ± 1.6
800	17.14	16.1	0.382	6.5	99.8	433.9 ± 0.1
880	17.25	14.4	0.411	7.6	99.8	436.4 ± 0.3
950	17.34	15.6	0.332	10.7	99.8	438.5 ± 0.7
1020	17.40	15.8	0.026	11.4	99.9	440.0 ± 0.2
1080	17.45	11.4	0.330	11.9	99.8	441.0 ± 0.6
1150	17.50	9.5	0.125	11.5	99.9	442.1 ± 0.4
1200	17.53	13.0	0.380	10.8	99.8	442.6 ± 0.2
1260	17.59	14.0	0.400	11.3	99.8	444.0 ± 0.5
1320	17.66	22.3	0.500	9.2	99.8	445.5 ± 0.4
1400	17.80	101.1	2.364	3.6	99.5	447.5 ± 0.6
Fuse	18.34	588.9	20.761	1.1	96.6	447.5 ± 2.4
Total gas age				100.0		440.0 ± 4.0
No plateau						

For total gas and plateau ages the total age uncertainty, including estimated uncertainties in the J-value and other systematic errors, are given so that results from different samples may be compared to each other and to results from other laboratories. For individual increments the uncertainty given includes only intralaboratory analytical uncertainty.

1993) are not considered likely here because petrographic evidence and mineral chemistry confirm that only a single stage of phengite growth occurred.

The three release spectra show different amounts of discordance (Fig. 5). This implies that the cause of the discordance affected the samples to different degrees. The parameters critical to a slow cooling model, namely grain size and cooling rate, are similar for the three samples and so this model would not predict the observed variation in discordance. On the other hand, parameters which would favour partial argon loss, namely late deformational features, do affect the samples to different degrees. Sample ATL-35, which is least affected by the late deformation, also gives the least discordant spectrum. Therefore, we assume that the most likely cause for the mild discordance in the release spectra is partial argon loss along deformation-induced dislocation networks within previously cooled grains. Both ATL-34 and KVA-57 show microscopic deformational features attributed to Scandian thrusting and/or later extension. We believe that these deformational events, which post-date the metamorphic mineral growth in the

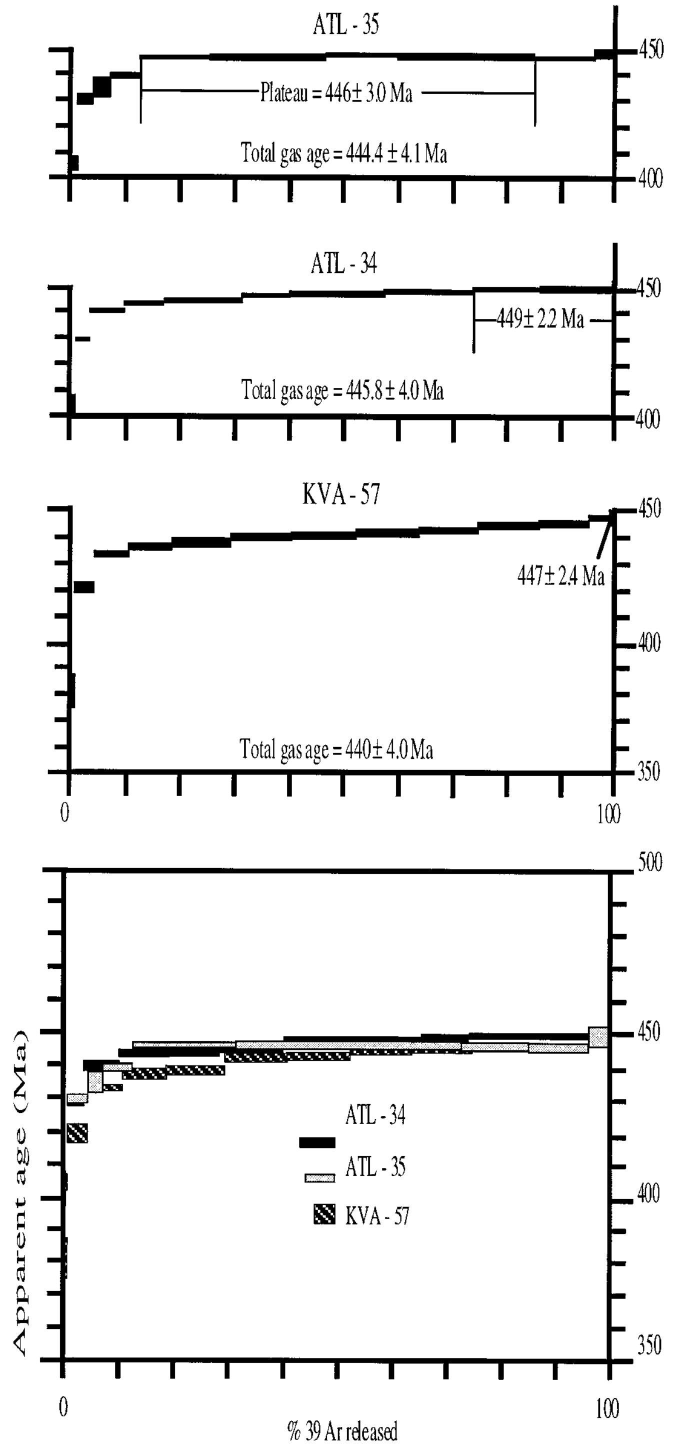

Fig. 5. (**a**) ^{40}Ar/^{39}Ar incremental release spectra for phengites from the Høyvik Group. The size of each rectangle represents the analytical uncertainty. (**b**) Superimposed release spectrums showing the samples are the same age within the uncertainty for high temperature increments. Sample KVA-57 gives younger apparent ages for increments released at lower extraction temperatures.

Høyvik Group, allowed some radiogenic ^{40}Ar to escape. In both cases the small range in apparent ages over most of the sample indicates that the fraction of argon lost was small. In such cases with a small amount of loss, the maximum apparent ages closely approximate the cooling age, but the time of disturbance cannot be resolved by the incremental release method.

With the exception of the Devonian sediments all the Caledonian rocks in the Sunnfjord area were affected by the Scandian, sub-garnet grade metamorphism. The Høyvik Group was clearly exposed to this weak thermal event, but meta-psammites collected in the present study did not recrystallise retrograde minerals and the pre-Scandian deformational micro-structures were not annealed. It is possible, however, that the apparent age gradient shared by all three samples in the first 10% of gas released (Fig. 5b) might reflect a small amount of argon loss due to thermal disturbance at that time.

In accordance with the interpretation of their release spectra as argon loss profiles, the minimum cooling ages of ATL-34 and KVA-57 are 449.1 ± 2.2 and 447.5 ± 4.0 Ma, respectively. These ages agree within uncertainties with the plateau age of 446.1 ± 3.0 Ma for ATL-35, suggesting that the three samples cooled at the same time. The greater fraction of argon loss inferred from the release spectrum for KVA-57 explains why its total gas age is somewhat younger than those of the other two samples, and emphasizes that its calculated total gas age does not date a geologic event.

An ^{40}Ar/^{39}Ar phengite age of 448 ± 8 Ma, consistent with the results presented above (see also Fig. 3), has recently been obtained by Eide *et al.* (1997) from the Høyvik Group close to the nonconformity with the Dalsfjord Suite north of Askvoll (Fig. 2).

Discussion and significance for the tectonics of the Scandinavian Caledonides

The Caledonian mountain belt in Scandinavia produced by the Scandian collision was of comparable size to the Himalayas, forming a belt more than 1700 km long in which nappe complexes comprising various pre-Scandian elements were thrust hundreds of kilometres southeastward onto Baltica. The marginal thrust belts of the orthogonal collision zone between Scandinavia and Greenland were separated by a wide hinterland region in which exhumed late Caledonian high-pressure provinces reveal evidence of extreme crustal thicknesses during the terminal stages of the continental collision (Griffin & Brueckner 1985; Andersen *et al.* 1991; Brueckner & Gillotti 1993; Gillotti 1993). The thrusting and folding in the foreland post-dates deposition of Late Silurian sandstones of the Oslo area and is probably of Early Devonian age, younger than *c.* 417 Ma (base Devonian, Tucker & McKerrow 1995). Palaeomagnetic evidence is consistent with the large-scale plate motions. Convergence at an average latitudinal drift-rate for Baltica on the order of 8–10 cm a^{-1} closed the Iapetus Ocean and resulted in near orthogonal continent–continent collision between Baltica and Laurentia in the Mid-Silurian to Early Devonian, with convergence between Baltica and Laurentia continuing into the Early Devonian (Torsvik *et al.* 1996).

By contrast, a model for the pre-Scandian tectonic development of the Scandinavian Caledonides is more elusive (Stephens *et al.* 1993). Part of the difficulty comes from the profound reworking of the older tectonic elements by Scandian events. The undoubtedly complex pre-Scandian history of the Scandinavian Caledonides is therefore constrained by only fragmentary evidence. Furthermore, it has proven difficult to relate events affecting the foreland, based on stratigraphic age control, to tectonic activity affecting the continental margin, dependent largely on isotope thermochronology. The Atløy and the Otta areas represent the only well documented unconformities demonstrating pre-Scandian tectonic activity in rocks suspected to have existed along the continental margin of Baltica. Well-preserved stratigraphic evidence of pre-Silurian orogenic events, as illustrated by the sub-Herland Group unconformity, is exceptional.

In the foreland, platformal sediments show some evidence of pre-Silurian deformation by their sedimentary facies. Llandeilian deposits in the Oslo area with high Ni and Cr contents (Bjørlykke 1974) may have been eroded from ophiolitic rocks obducted onto the Caledonian margin of Baltica in the Early Ordovician (Sturt 1984). Andresen (1982) related the massive sandstones, underlying limestones of Arenig age on Hardangervidda (Fig. 1) to uplift of a westerly source area (pheripheral bulge) produced by emplacement of Caledonian nappes further to the west. At Høgberget (Fig. 1) eastern Norway, Cambrian platformal sediments are missing between Late Proterozoic sparagmites (Ring Formation) and Arenig–Llanvirn (?) limestones (Nystuen 1975). In the transitional zone between the Lower and Middle Allochthon in the Valdres area and in the Jämtland Supergroup of Sweden (Gee *et al.* 1985), Llandeilian changes in sedimentary facies have been interpreted to reflect subsidence in a foreland basin as a result of thrust-loading of the most distal parts of the Caledonian margin of Baltica. Presumably these stratigraphic effects may be related to Tremadoc (or possibly older) obduction and emplacement of ophiolite and arc complexes.

Near Otta (Fig. 1), mapping has shown that the Vågåmo ophiolite was obducted onto miogeoclinal Late Proterozoic cover rocks (sparagmites) above basement considered to be of Baltic affinity (Sturt & Roberts 1991; Sturt *et al.* 1991, 1995; Bøe *et al.* 1993; Bjerkgård & Bjørlykke 1994). Based on fossil evidence in the unconformable Sel Group (Bruton & Harper 1981), obduction apparently occurred prior to the Arenig–Llanvirn boundary (*c.* 470 Ma) (Sturt *et al.* 1991). A U–Pb zircon age of 488 ± 2 Ma (Bjerkgård & Bjørlykke 1994) from a quartz-diorite intruding rocks in the Foldal area (Fig. 1) and regarded to be stratigraphic equivalents to the Sel Group, indicates that the obduction was of Tremadoc or older age (Sturt *et al.* 1995).

Isotopic results from rocks of the Middle and Upper Allochthons of the central Scandinavian Caledonides (see summary by Andréasson 1994) suggest that rocks believed to have formed parts of the outer margin of Baltica (Stephens & Gee 1987), were affected by an early Caledonian orogenic event. This event included depression of transitional oceanic–continental crust and miogeoclinal rocks to depths of at least 50 km as recorded by the eclogite facies metamorphic rocks of the Seve Nappes (Kullerud *et al.* 1990; Andréasson 1994). Sm–Nd mineral isochrons from eclogites gave ages of 505 ± 14 and 505 ± 18 Ma (Mørk *et al.* 1988), i.e. a Mid-Cambrian to Tremadoc age. Because the eclogites in the Seve Nappes occur at a structural position higher than those of the Western Gneiss Region, it is reasonable to assume that these eclogites were formed by a different and older tectonic event than the Scandian phase that produced eclogites in the structurally underlying Western Gneiss Region.

U–Pb analyses of metamorphic titanite and monazite from localities in the Seve Nappe gave ages of *c.* 435–440 Ma (Gromet *et al.* 1993), significantly younger than the Early Ordovician age inferred from hornblende ^{40}Ar/^{39}Ar release spectra from the same localities by Dallmeyer *et al.* (1985). This example illustrates the opportunity for conflicting interpretations in complex rocks without stratigraphic age control.

In the Bergen area (Fig. 1), eclogites of the Lindås Nappe occur in the hanging wall of the extensional Fensfjorden shear zone (Wennberg 1996). These rocks are structurally positioned above the Western Gneiss Region eclogites. Based on some few ^{40}Ar/^{39}Ar ages, Boundy *et al.* (1996) have suggested that cooling of the Lindås Nappe eclogites through the closure temperatures for Ar diffusion in amphibole and muscovite took place at *c.* 448 and *c.* 430 Ma respectively (Fig. 6).

The polyphase nature of the Caledonian tectonic evolution is well established from the ophiolite and arc terranes of the Upper Allochthon (Fig. 6). Detailed geochemistry combined with precise U–Pb geochronology (497 ± 2 to 470^{+9}_{-5} Ma) demonstrates that the studied ophiolite and island-arc terranes formed in an intra-oceanic supra-subduction zone setting in the Late Cambrian to Ordovician (Arenig/Llanvirn) (Pedersen 1992). Many of these complexes are unconformably overlain by sedimentary and volcanic sequences of Ordovician to early Silurian or in some cases unknown age (Sturt *et al.* 1985). These ophiolite- and arc-lithologies have been referred to as ‘Group 1’ ophiolites (Sturt 1984; Furnes *et al.* 1985). Sturt (1984) argued that obduction and emplacement of ‘Group 1’ ophiolites onto the Baltic continental margin occurred during a late Cambrian–Early Ordovician orogenic event often referred to as the Finnmarkian phase (Sturt *et al.* 1978). Some large mafic/ultramafic complexes and ophiolites without unconformable Ordovician sequences were referred to as ‘Group 2’ ophiolites. In view of the well-constrained ages available from some of the ophiolite/arc complexes (Pedersen 1992), it does not appear that the pre-Scandian history can be explained by a single obduction event in Late Cambrian/Tremadoc time since some of the ‘Group 1’ ophiolites (Karmøy, Bømlo and Bergen area) are younger or contain younger oceanic elements. Therefore, we suggest that a model with two distinct ophiolite-generating events may be too simple. Some of the ophiolite complexes such as the Vågåmo and Støren ophiolites were obducted in Late Cambrian/Tremadoc time as shown by Sturt and co-workers. This event may be responsible for the high-pressure metamorphism preserved in the Seve nappe in the Swedish Caledonides. But a variety of other ophiolite and island-arc complexes of the Upper Allochthon, containing important Arenig to Llanvirn volcanic-arc elements (Pedersen 1992), younger Ordovician to Silurian rift-related mafic rocks previously referred to as Group 2 ophiolites, as well as granitoid intrusions may have formed in a mature intra-oceanic arc complex that was accreted to Baltica later and emplaced into its pre-extension position during the Scandian orogeny (Andersen & Andresen 1994).

From palaeomagnetic data, Torsvik *et al.* (1991) suggested that pre-Scandian deformation along the Caledonian margin of Baltica may have been associated with large-scale anticlockwise rotation of Baltica in Early to Mid-Ordovician time. More recently Torsvik *et al.* (1996) suggested that the Cambrian to Early Ordovician tectonic activity along the Caledonian margin of Baltica took place when Baltica was facing a 1200–1500 km wide ocean separating Baltica and Siberia, rather than facing the Iapetus ocean separating Baltica and the Appalachian margin of Laurentia. The work by Torsvik and co-workers necessitates more complex models for the tectonic evolution and accretion of outboard terranes to Baltica than implicit in less mobilistic ‘Wilson cycle’ tectonics advocating an origin of these oceanic complexes in the Iapetus Ocean (Sturt *et al.* 1984; Pedersen & Dunning 1991; Pedersen 1992). Even allowing for some uncertainty in calibrating

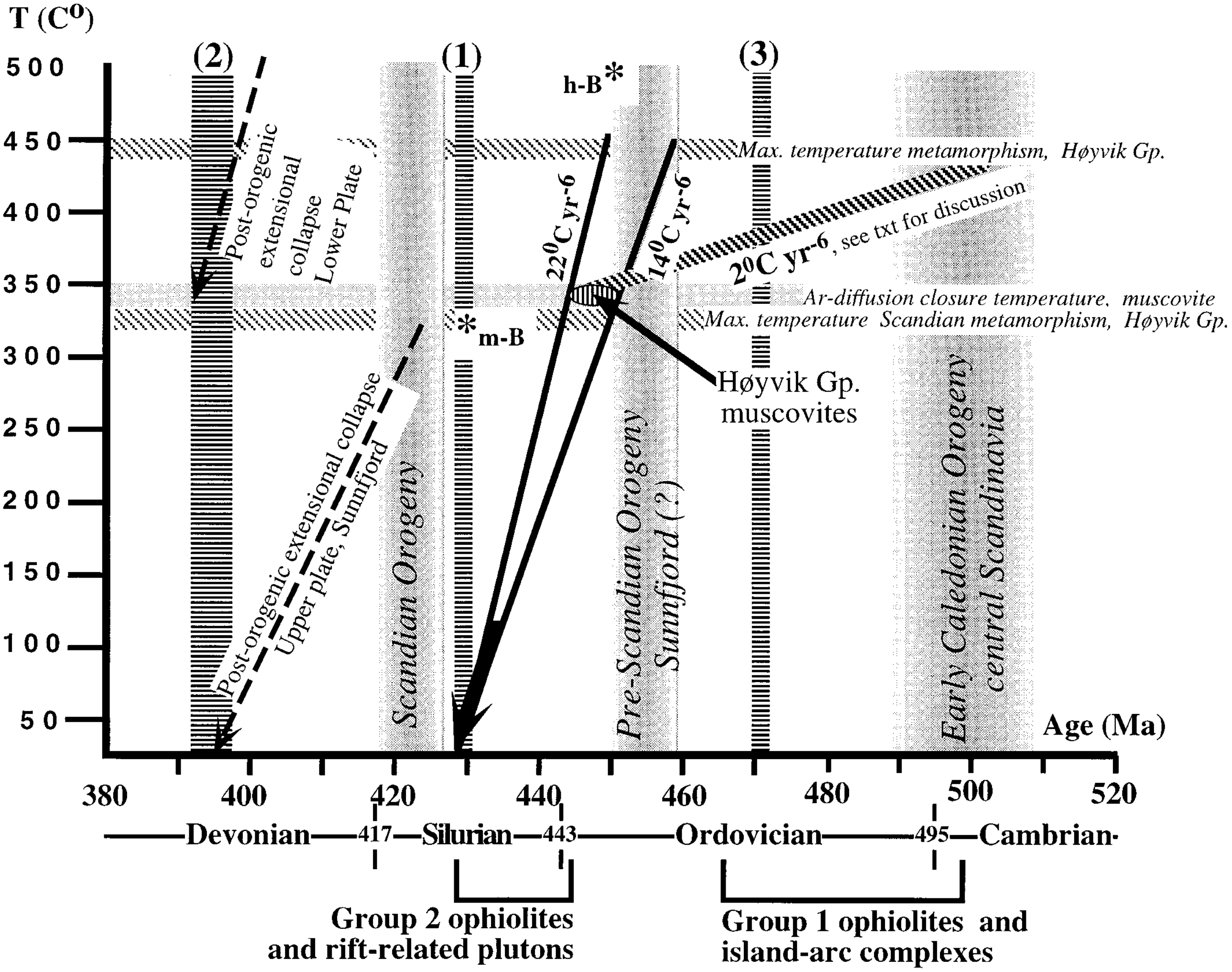

Fig. 6. Temperature–time paths in the Sunnfjord area, showing cooling rates of the pre- and post-Scandian evolution. The ages of unconformities and orogenic events discussed in the text are shown or indicated when considered uncertain. ^{40}Ar/^{39}Ar ages, hornblende h-B*, and muscovite *m-B, from the Bergen area are after Boundy *et al.* (1996). The age of the ophiolites/rift related mafic complexes are from Pedersen (1992). Numbers (1), (2) & (3) shows the ages of the unconformities under the Herland Group, The Devonian Basins and the Sel Group.

isotopic and stratigraphic ages, it is difficult to see how some of the 'Group 1' ophiolites (Karmøy, Bømlo and Bergen Arc areas) could have been obducted in a Tremadoc or earlier event since their post-Tremadoc magmatic evolution apparently was related to an oceanic history (Pedersen 1992).

Based on mineral assemblages, mineral textures and microstructures, and phengitic compositions of the white micas, it is likely that Høyvik Group rocks never achieved temperatures above 450°C. The peak metamorphic temperature did not exceed the closure temperature for volume diffusion of argon through phengite, which we take to be approximately 350°C, by more than 100°C (Dahl 1996). The data obtained in this study show that the Høyvik Group phengites closed to Ar diffusion at 447 ± 4 Ma (uncertainty when all samples are considered), corresponding to latest Caradoc or Ashgill time. The rocks were exhumed to surface conditions (*c.* 20°C) before deposition of the fossiliferous Herland Group of Wenlock age (423–428 Ma). Comparing these temperatures at these two times gives a rapid average cooling rate for the Høyvik Group of between 14 and 22°C/Ma^{-1} during a period of 20 Ma in the Late Ordovician (Ashgill)–Early Silurian (Llandovery). If the rocks had been cooling at a similar rate before reaching the phengite closure temperature, then peak temperatures (*c.* 450°C) would have existed only a short time and most probably less than 10 Ma before the ages obtained for the Høyvik Group phengites (Fig. 6). So, for an approximately constant cooling rate, the maximum temperature during the pre-Scandian event must have occurred at *c.* 458 Ma or younger (Caradoc). The combination of low peak temperatures and rapid cooling rate suggest that while the ^{40}Ar/^{39}Ar phengite ages from the Høyvik Group are strictly interpreted as the time of cooling, it is likely that the ages obtained in this study closely approximate the time of prograde metamorphic mineral growth. This implies that the orogenic event that affected the Høyvik Group together with its Dalsfjord Suite basement was of Mid- or Late Ordovician age. While this is similar to some metamorphic ages reported for the Lindås Nappe (Boundy *et al.* 1996) and ages from the Seve Nappe (Gromet *et al.* 1993), it is significantly younger than Cambrian to Early Ordovician events affecting continental rocks of Baltica and of suspected Baltic affinity that have been documented from south-central Norway and the Swedish Caledonides.

In order for the Late Ordovician cooling ages from the Høyvik Group to be related to the Cambrian–Early Ordovician events, it would require that the rocks remained at nearly constant temperature and pressure conditions for at least the 40 Ma from Tremadoc until the beginning of Ashgill time. Such a model would imply that the exhumation and cooling rate must have increased abruptly from less than 2°C Ma^{-1} in the Early to Mid-Ordovician, to between 14 and 22°C Ma^{-1} in the Late Ordovician to Early Silurian (Fig. 6). Such a protracted, virtually static, condition seems unlikely, especially considering the dynamic nature of tectonic events on the Baltic margin and outboard terranes during the Ordovician.

Conclusions

^{40}Ar/^{39}Ar ages from phengitic muscovite show that the pre-Silurian Høyvik Group between Dalsfjorden and Førdefjorden in West-Norway cooled through the temperature for argon retention in phengite at 447 ± 4 Ma. Thermal effects during Scandian orogeny and post-orogenic extension were not sufficient to cause widespread disturbance of the Ar isotopes in white micas preserved in the upper plate of the Nordfjord–Sogn Detachment in this area. Minor discordance of some Ar-spectra implies that one or both of these tectonic events may have caused some radiogenic ^{40}Ar to escape from certain rocks, probably controlled by localised, grain-scale deformation. The small range in apparent ages within and among samples indicates that the argon loss was small. While rocks in the hanging wall of the Nordfjord–Sogn Detachment were virtually unaffected by Silurian to Devonian metamorphism, gneisses in the footwall were metamorphosed to high grade, including eclogites along Dalsfjorden and Førdefjorden. This sharp break in thermal history shows that a significant amount of transport occurred along the detachment during the post-orogenic extension.

The thermochronologic results integrated with the stratigraphic evidence in the hanging wall of the Nordfjord–Sogn Detachment demonstrate very rapid cooling and exhumation in the Early Silurian, by which some Late Ordovician metamorphic rocks were exposed to the surface by Wenlock time. This is apparently consistent with high cooling rates in the Early Silurian from eclogites of the Lindås Nappe of the Bergen area (Boundy *et al.* 1996). The rapid cooling and exhumation event was contemporaneous with formation of ‘Group 2’ ophiolites and major extension-related mafic plutons in the Scandinavian Caledonides, but significantly post-dates other pre-Scandian Caledonian events on Baltica (Fig. 6).

Stephens *et al.* (1993) and Andersen & Andresen (1994) have previously indicated that simplistic two stage (Finnmarkian and Scandian) models are no longer tenable for the orogenic evolution of the outboard terranes of the Scandinavian Caledonides. The Late Ordovician cooling ages from the Høyvik Group suggest that similar caution should be exercised when dealing with terranes suspected to be of Baltic affinity, and that a more complex tectonic scenario than a two stage orogenic evolution of the Caledonian margin of Baltica may be required.

This study was financially supported through grants from the Norwegian Research Council (to T.B.A. and A.A.), Norsk Agip (to T.B.A.) and the National Science Foundation (to H.N.B. and D.R.L.). The project was conceived during an NSF-NATO Fellowship (to H.N.B.). Laboratory assistance by D. P. West and probe analysis by A. V. McGuire and M. D. Dyar are gratefully acknowledged. This paper has benefited from discussions with D. P. West and C. V. Guidotti and was improved by a careful review by E. Eide.

References

ALEXANDER, E.C., MICHELSON, G.M. & LANPHERE, M.A. 1978. A new 40Ar/39Ar dating standard. *In*: ZARTMAN, R. E. (ed.) *Short Papers of the Fourth International Conference on Geochronology, Cosmochronology and Isotope Geology*. US Geological Survey Open-File Report, **78–701,** 6–8.

ANDERSEN, T.D. & ANDRESEN, A. 1994. Stratigraphy, tectonostratigraphy and accreation of outboard terranes in the Caledonides of Sunnhordland, W. Norway. *Tectonophysics,* **231,** 71–84.

—— & DÆHLIN, P.C. 1986. Basement-cover kontakten mellom Høyvikgruppen og Dalsfjordsuiten på Atløy, en pre-kaledonsk avsetningskontakt. *Geolognytt,* **21,** 13.

—— & JAMTVEIT, B. 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,** 1097–1111.

——, JAMTVEIT, B., DEWEY, J.F. & SWENSSON, E. 1991. Subsduction and eduction of continental crust: major mechanism during continent-continent collision and orogenic extensional collapse, a model based on the south Norwegian Caledonides. *Terra Nova,* **3,** 303–310.

——, OSMUNDSEN, P.T. & JOLIVET, L. 1994. Deep crustal fabrics and a model for the extensional collapse of the southwest Norwegian Caledonides. *Journal of Structural Geology,* **147,** 59–68.

——, SKJERLIE, K.P. & FURNES, H. 1990. The Sunnfjord Melange, evidence for a Silurian ophiolite accretion in the West Norwegian Caledonides. *Journal of the Geological Society of London,* **147,** 59–68.

ANDRÉASSON, P.G. 1994. The Baltoscandian Margin in Neoproterozoic-Early Palaeozoic time. Some constraints on terrane derivation and accretion in the Arctic Scandinavian Caledonides. *Tectonophysics,* **231,** 1–32.

ANDRESEN, A. 1982. *Stratigraphy and structural history of the Lower Palaeozoic metasediments on Hardangervidda, South Norway*. PhD thesis, University of California, Davis.

AUSTRHEIM, H. 1987. Eclogitization of lower crustal granulites by fluid migration through shear zones. *Earth and Planetary Science Letters,* **81,** 221–232.

BERRY, H.N., LUX, D.R., ANDRESEN, A. & ANDERSEN, T.B. 1993. Argon 40/39 dating of rapidly uplifted high-pressure rocks during late-orogenic extension in southwest Norway. *Geological Society of America Abstracts with Program,* **25.**

——, ——, —— & —— 1994. Progressive exhumation during orogenic collapse as indicated by 40/39 Ar cooling ages from different structural levels, southwest Norway. *Geonytt,* **22,** 1, 20–21.

BJERKGÅRD, T. & BJØRLYKKE, A. 1994. Geology of the Foldal area, Southern Trondheim Region Caledonides, Norway. *Norges Geolgoiske Undersøkelse, Bulletin,* **426,** 53–75.

BJØRLYKKE, K. 1974. Depositional history and geochemical composition of Lower Palaeozoic epicontinental sediments from the Oslo Region. *Norges Geologiske Undersøkelse, Bulletin,* **305,** 1–81.

BOUNDY, T.M., ESSENE, E.J., HALL, C.M., AUSTRHEIM, H. & HALLIDAY, A.N. 1996. Rapid exhumation of lower crust during continent-continent collision and late extension: Evidence from ^{40}Ar/^{39}Ar incremental heating of hornblendes and muscovites, Caledonian orogen, western Norway. *Geological Society of America Bulletin,* **108,** 1425–1437.

BREKKE, H. & SOLBERG, P.O. 1987. The geology of Atløy, Sunnfjord, western Norway. *Norges Geologiske Undersøkelse, Bulletin,* **410,** 73–94.

BRUECKNER, H.K. & GILOTTI, J. 1993. Preliminary age constraints on the timing of eclogite facies metamorphism, Northeast Greenland Caledonides. *Geological Society of America Abstracts with Program,* **25,** A 340.

BRUTON, D.L. & HARPER, D.A.T. 1981. Brachiopods and trilobites of the early Ordovician serpentinite Otta conglomerate, south central Norway. *Norsk Geologisk Tidsskrift,* **61,** 153–181.

BØE, R., STURT, B.A. & RAMSAY, D.M. 1993. The conglomerates of the Sel Group, Otta-Vågå area, Central Norway: an example of a terrane-linking succession. *Norges Geologiske Undersøkelse Bulletin,* **425,** 1–23.

COSTA, S. & MALUSKI, H. 1988. Use of the 40Ar-39Ar stepwise heating method for dating mylonite zones: An example from the St. Barthelemy Massif (northern pyrenees, France). *Chemical Geology, Isotope Geoscience Section,* **72,** 127–144.

DAHL, P.S. 1996. The crystal-chemical basis for Ar retention in micas; inferences from interlayered partitioning and implications for geochronology. *Contributions to Mineralogy and Petrology,* **123,** 22–39.

Dallmeyer, R.D., Andreasson, P.G. & Svenningsen, O. 1991. Initial tectonothermal evolution within the Scandinavian Caledonide Accretionary Prism: constraints from 40Ar/39Ar mineral ages within the Seve Nappe Complex, Sarek Mountains, Sweden. *Journal of Metamorphic Geology,* **9,** 203–218.

——, Gee, D.G. & Beckhomen, M. 1985. 40Ar/39Ar mineral age record of early Caledonian tectonothermal activity in the Baltoscandian miogeocline. *American Journal of Science,* **285,** 532–568.

Dalrymple, G.B. & Lanphere, M.A. 1969. *Potassium-argon dating*. W.H. Freeman, San Fransico.

——, Alexander, E.C., Lanphere, M.A. & Kraker, G.P. 1981. *Irradiation of samples for ^{40}Ar/^{39}Ar dating using the Geological Survey TRIGA reactor*. US Geological Survey Professional Paper.

Dodson, M.H. 1973. Closure temperature in cooling geochronological and petrological systems. *Contributions to Mineralogy and Petrolology,* **40,** 259–274.

Dunning, G.R. & Pedersen, R.B. 1988. U/Pb ages of ophiolites and arc-related plutons of the Norwegian Caledonides: implications for the development of Iapetus. *Contributions to Mineralogy and Petrology,* **98,** 13–23.

Dæhlin, P.C. & Andersen, T.B. 1988. Deformation and stratigraphy of the Høyvik Group, Sunnfjord. *Intern skriftserie, Department of Geology, University of Oslo,* **54,** 12–14.

Eide, E.A., Torsvik, T.H. & Andersen, T.B. 1995. Absolute dating of brittle movements: Late Permian and Late Jurasssic fault extensional fault breccias in western Norway. *Terra Nova,* **9,** 135–139.

Furnes, H., Pedersen, R.B., Sundvoll, B., Tysseland, M. & Tumyr, O. 1989. The age, geochemistry, and tectonic setting of the late Caledonian G søy intrusion, west Norway. *Norsk Geologisk Tidsskrift,* **69,** 273–289.

——, Ryan, P.D., Grenne, T., Roberts, D., Sturt, B.A. & Prestvik, T. 1985. Geological and geochemical classification of the ophiolite fragments in the Scandinavian Caledonides. *In*: Gee, D.G. & Sturt, B.A. (eds) *The Caledonide Orogen—Scandinavia and related areas*. Wiley, New York, 657–670.

——, Skjerlie, K.P., Pedersen, R.B., Andersen, T.B., Stillman, C.J., Suthren, R., Tysseland, M. & Garmann, L.B. 1990. The Solund-Stavfjord Ophiolite Complex and associated rocks, west Norwegian Caledonides: Geology, geochemistry and tectonic environment. *Geological Magazine,* **27,** 209–224.

Gee, D.G., Guezou, J.-C., Roberts, D. & Wolff, F.C. 1985. The central-southern part of the Scandinavian Caledonides. *In*: Gee, D.G. & Sturt, B.A. (eds) *The Caledonide Orogen – Scandinavia and related areas*. Wiley, New York, 109–133.

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

Griffin, W.L. & Brueckner, H.K. 1985. REE, Rb-Sr and Sm-Nd studies of Norwegian eclogites. *Chemical Geology,* **52,** 249–271.

Gromet, P.L., Bergman, S., Sjøstrøm, H. & Claesson, S. 1993. High-presision metamorphic U-Pb ages in the Seve Nappes, Scandinavian Caledonides of central Sweden. *Geological Society of America Abstracts with Programs,* **25,** A340.

Guidotti, C.V. 1969. A comment on "Chemical study of minerals from the Moine Schists of the Ardnamurchan area, Argyllshire, Scotland" by B.C.M. Butler, and its implications for the phengite problem. *Journal of Petrology,* **10,** 164–170.

Guidotti, C.V. 1984. Micas in metamorphic rocks. *In*: Baily, S.W. (ed.) *Micas.* Mineralogical Society of America, Reviews in Mineralogy, **13,** 357–468.

Hames, W.E. & Hodges, K.V. 1993. Laser 40Ar/39Ar evaluation of slow cooling and episodic loss of 40Ar from a sample of polymetamorphic muscovite. *Science,* **261,** 1721–1723.

Kolderup, N.H. 1921. *Der Mangeritsyenit und umgebende Gesteine in Søndfjord.* Bergens Museum Årbok, Matematisk-Naturvitenskapelig Serie.

Kullerud, K., Stephens, M.B. & Zachrisson, E. 1990. Pillow lavas as protolith for eclogites: evidence from a late Precambrian-Cambrian continental margin, Seve Nappes, Scandinavian Caledonides. *Contributions to Mineralogy and Petrology,* **105,** 1–10.

Lanphere, M.A. & Albee, A.L. 1974. 40Ar/39Ar age measurements in the Worcester Mountain: Evidence of Ordovician and Devonian metamorphic events in northern Vermont. *American Journal of Science,* **274,** 545–555.

McDougall, I. & Harrison, T.M. 1988. *Geochronology and thermochronology by the 40Ar/39Ar Method.* Oxford University Press.

Merrihue, C.M. & Turner, G. 1966. Potassium-argon dating by activation with fast neutrons. *Journal of Geophysical Research,* **71,** 2852–2857.

Mørk, M.B.E., Kullerud, K. & Stabel, A. 1988. Sm-Nd dating of Seve eclogites, Norrbotten, Sweden – Evidence for early Caledonian (505 Ma) subduction. *Contributions to Mineralogy and Petrology,* **99,** 344–351.

Norton, T.H. 1986. Late Caledonian extension in western Norway: a response to extreme crustal thickening. *Tectonics,* **5,** 192–204.

Nystuen, J.P. 1975. *Elvdal.* Mapsheet, 2018 II, 1:50.000. Norges Geologiske Undersøkelse.

Osmundsen, P.T. 1996. *Late-orogenic structural geology and Devonian basin formation in Western Norway: A study from the hanging wall of the Nordfjord-Sogn Detachment in the Sunnfjord Region.* Dr. Scient. thesis, University of Oslo.

—— & Andersen, T.B. 1994. Caledonian compressional and late-orogenic extensional deformation in the Staveneset area, Sunnfjord, Western Norway. *Journal of Structural Geology,* **16,** 1385–1401.

Pedersen, R.B. 1992. Geochronology, Geochemistry and Petrogenesis of Caledonian Ophiolite Complexes. Dr. philos. thesis, University of Bergen.

—— & Dunning, G. 1991. U/Pb datering av øybuemagmatisme innenfor det sørvest-norske ofiolitt-terreng. *Geonytt,* **1,** 42–43.

Roberts, D. & Gee, D.G. 1985. An introduction to the structure of the Scandinavian Caledonides. *In*: Gee, D. G. & Sturt, B.A. (eds). The Caledonide Orogen—Scandinavia and related areas. Wiley, New York, 485–497.

Ross, J.A. & Sharp, W.D. 1988. The effects of sub-blocking temperature metamorphism on the K/Ar systematics of hornblendes: 40Ar/39Ar dating of polymetamorphic garnet amphibolite from the Fransican Complex, California. *Contributions to Mineralogy and Petrology,* **100,** 213–221.

Séranne, M. & Séguret, M. 1987. The Devonian basins of western Norway: Tectonics and kinematics of extending crust. *In*: Coward, M.P., Dewey, J.F. & Hancock, P.L. (eds) *Continental extensional tectonics.* Geological Society, London, Special Publications, **28,** 537–548.

Steiger, R.H. & Jäger, E. 1977. Subcomission on geochronology convention on the use of decay constants in geo- and cosmochronology. *Earth and Planentary Science Letters,* **36,** 359–362.

Stephens, M.B., Kullerud, K. & Claesson, S. 1993. Early Caledonian tectonothermal evolution in outboard terranes, central Scandinavian Caledonides: new constraints from U-Pb zircon dates. *Journal of the Geological Society, London,* **150,** 51–56.

—— & Gee, D.G. 1987. Terranes and polyphase accretionary history in the Scandinavian Caledonides. *Geological Society of America, Special Papers,* **230,** 17–30.

Sturt, B.A. 1984. The accretion of ophiolite terrains in the Scandinavian Caledonides. *Geologije en Mijnbouw,* **63,** 201–212.

—— & Roberts, D. 1991. Tectonostratigraphic relationships and obduction histories of Scandianavian ophiolite terranes. *In*: Peters, T., Nicolas, A. & Coleman, R.J. (eds) *Ophiolite genesis and evolution of the oceanic lithosphere.* Kluwer Academic Publisher, 745–769.

——, Andersen, T.B. & Furnes, H. 1985. The Skei Group, Leka: an unconformable clastic sequence overlying the Leka Ophiolite. *In*: Gee, D.G. & Sturt, B.A. (eds) *The Caledonide Orogen—Scandinavia and related areas*. Wiley, New York, 395–405.

——, Bøe, R., Ramsay, D.M. & Bjerkgård, T. 1995. Stratigraphy of the Otta-Vågå tract and regional stratigraphic implications. *Norges Geologiske Undersøkelse, Bulletin,* **427,** 25–28.

——, Pringle, I.R. & Ramsay, D.M. 1978. The Finnmarkian phase of the Caledonian orogeny. *Journal of the Geological Society, London,* **135,** 597–610.

——, Ramsay, D.M. & Neuman, R.B. 1991. The Otta conglomerate, the Vågåmo Ophiolite—further indications of early Ordovician orogenesis in the Scandinavian Caledonides. *Norsk Geologisk Tidsskrift,* **71,** 107–115.

——, Roberts, D. & Furnes, H. 1984. A conspectus of Scandinavian Caledonian ophiolites. *Geological Society of London. Special Publication,* **13,** 381–390.

Svenningsen, O.F. 1993. *Tectonic evolution of the Sarektjåkka nappe, northern Swedish Caledonides*. PhD thesis, University of Lund.

Torsvik, T.H., Ryan, P.D., Trench, A. & Harper, D.A.T. 1991. Cambrian-Ordovician palaeogeography of Baltica. *Geology,* **19,** 7–10.

——, Smethurst, M.A., Meert, J.G., Van der Voo, R., McKerrow, W.S., Brasier, M.D., Sturt, B.A. & Walderhaug, H.J. 1996. Continental break-up and collision in the Neoproterozoic and Palaeozoic—A tale of Baltica and Laurentia. *Earth-Science Reviews,* **40,** 229–258.

——, Sturt, B.A., Swensson, E., Andersen, T.B. & Dewey, J.F. 1992. Palaeomagnetic dating of fault rocks: Evidence for Permian and Mesozoic movements along the Dalsfjord Fault, Western Norway. *Geophysical Journal International,* **109,** 565–580.

Tucker, R.D. & McKerrow, W.S. 1995. Early Palaeozoic chronology: a review in light of new U-Pb zircon ages from Newfoundland and Britain. *Canadian Journal of Earth Sciences,* **32,** 368–379.

Turner, G. 1968. The distribution of potassium and argon in chondrites. *In*: Ahrens, L.H. (ed.) *Origin and distribution of elements.* International Monographs on Earth Sciences, **30**. Pergamon, Oxford, 387–398.

Villa, I.M. & Zeitler, P.K. 1988. Ar diffusion in partially outgassed alkali feldspars; insights from (super 40) Ar/ (super 39) analysis; discussion and reply. *Chemical Geology, Isotope Geoscience Section,* **73,** 265–269.

Wennberg, O.P. 1996. Superimposed facbrics due to reversals of shear sense: an example from the Bergen Arc Shear Zone, western Norway. *Journal of Structural Geology,* **18,** 871–889.

West, D.P. Jr & Lux, D.R. 1993. Dating of mylonite deformation by the 40Ar/39Ar method: An example from the Normubega fault zone, Maine. *Earth and Planetary Science Letters,* **120,** 221–237.

——, Ludman, A. & Lux, D.R. 1992. Silurian age for the Pocomoonshine Gabbro-Diorite, southeasten Maine and its regional tectonic implications. *American Journal of Science,* **292,** 253–273.

Received 13 February 1997; revised typescript accepted 24 October 1997.
Scientific editing by Simon Kelley.