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Timing and kinematics of Caledonian thrusting and extensional collapse, southern Norway: evidence from ^{40}Ar/^{39}Ar thermochronology

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Abstract—^{40}Ar/^{39}Ar dating methods have been applied to rocks across the Caledonian orogen in southwestern Norway. In the eastern nappe area, K-feldspar thermochronological modeling, microfabric characteristics and conodont color alteration together indicate that temperatures were not above the closure temperature of muscovite for any significant period of time. Two groups of muscovite and biotite ages from this area (415–408 for most samples with top-to-the-SE fabrics and 402–394 for samples with top-to-the-NW fabrics) are therefore interpreted as ages of contractional (thrusting) and extensional (hinterland-directed nappe translation) deformation, respectively. In the west (hinterland), peak Caledonian temperatures were higher, and ^{40}Ar/^{39}Ar plateau ages are generally interpreted as cooling ages. The western basement and lower nappes cooled rapidly through ~500°C (basement) at ~404 Ma and 350°C (basement and lower nappes) shortly after, i.e. during extensional top-to-the-NW transport of the orogenic wedge. In addition, tectonostratigraphically higher nappes in the hinterland show evidence of earlier cooling, probably following Ordovician orogenic activity prior to the main collisional stage. The new ^{40}Ar/^{39}Ar data conform to kinematic observations that contraction and extension in the Caledonian nappe region were sequential, and that the change from contraction (convergence) to extension (divergence) was quick (between 408 and 402 Ma). © 1998 Elsevier Science Ltd. All rights reserved

INTRODUCTION

It is now generally accepted that the complex tectonothermal evolutions of many orogenic belts, which were traditionally attributed to contractional deformation or plate convergence, are significantly influenced by syn- to post-orogenic extensional deformation and tectonics. A well-exposed example is the remnants of the Caledonian orogen in Scandinavia, where the basal thrust (décollement) zone recently was discovered to contain abundant kinematic indicators indicating a 'wrong' sense of shear with respect to thrusting (Fossen, 1992; Fossen and Rykkelid, 1992). In this particular example, extensional fabrics consistently overprint contractional fabrics at a regional scale, and the basal thrust zone was reactivated as a low-angle extensional detachment which was subsequently transected by somewhat steeper extensional shear zones. However, uncertainties exist about the absolute timing of the contraction and the different expressions of extensional deformation, as reflected in the recent literature (e.g. Andersen, 1993; Fossen, 1993a). We here present results from a transect across the Caledonide orogen in SW Norway that helps to constrain the tectonothermal history of the classical Caledonian nappe region in Scandinavia.

TECTONIC SETTING

Caledonian framework

Convergent motions of Laurentia (North America) and Scandinavia (Baltica) in Ordovician and Silurian times caused the creation of the Caledonian orogenic belt. The Caledonian orogeny is believed to have culminated by a continent–continent collision somewhat similar to the India–Asia example, where the western edge of Baltica (Western Gneiss Region) was subducted under orogenic terranes located between converging Laurentian and Baltic cratons. On the Scandinavian (Baltic) side, these motions formed a wedge consisting of Proterozoic and Lower Paleozoic rocks of both oceanic and continental affinities. Remnants of this orogenic wedge are preserved in a 1700-km-long and up to 350-km-wide orogenic belt along western Scandinavia (Bryhni and Sturt, 1985). Some of the nappes in this orogenic wedge were thrust for several hundred kilometers to the southeast, including the Jotun Nappe, which apparently represents a huge detached fragment of the pre-collisional continental margin of Baltica (Hossack and Cooper, 1986).

The orogenic wedge in Scandinavia is separated from the Precambrian basement (Fig. 1) by a mechanically weak décollement zone, consisting of phyllites, micaschists and other metasedimentary rocks that locally contain tectonic slivers of sheared basement rocks. The metasedimentary rocks are mostly of Vendian to Ordovician age, deposited on top of the basement prior to, and locally also during, Caledonian thrusting. A considerable amount of Caledonian deformation has been localized in this décollement zone. Caledonian deformation of the underlying basement is mostly restricted to the contact zone with the overlying décollement rocks and thus classifies as thin-skinned, except for the western parts (the Øygarden Complex and Western Gneiss Region; WGR) where significant but heterogeneous Caledonian deformation is also present within the basement.

The westernmost part of the orogenic wedge, of which only remnants are preserved, contain 'outboard terranes', i.e. Ordovician ophiolite fragments and island-arc related magmatic rocks with unconformably overlying sedimentary and volcanic sequences. There are indications that these ophiolitic rocks may have formed on the Laurentian side of the pre-collisional ocean (Iapetus) in the early Ordovician, and became amalgamated to Baltica during the final, Silurian, collision (Pedersen *et al.*, 1988). The rest of the allochthonous units are dominated by Proterozoic rocks that were detached from the hinterland during the history of convergence. In the study area, the Jotun Nappe constitutes the largest of these, with the Bergsdalen Nappes as smaller tectonics units (Fig. 1).

Increasing metamorphic grade in the (par)autochthonous cover from the foreland region towards the coastal area in the west (e.g. Lindquist, 1990) indicates an originally ESE-tapering, wedge-shaped geometry of the Caledonian nappe pile in Scandinavia. Similarly, the basement shows a westward increase in Caledonian *PT*-conditions, and Caledonian high-*P* eclogite parageneses in the westernmost part of the WGR are interpreted as indicating subduction of the western margin of Baltica to depths of 60–70 km or more during the Silurian continent–continent collision (Griffin *et al.*, 1985).

Kinematic history

Although SE-directed, contractional nappe displacements of several hundreds of kilometers have been estimated in southern Norway (e.g. Hossack *et al.*, 1985), detailed kinematic analysis of mylonitic fabrics in the décollement zone has revealed that the dominating sense of shear is top-to-the-(W)NW, i.e. opposite to that deduced from orogen-scale reconstructions. The latter shear deformation (D_2) consistently overprints and locally obliterates contractional top-to-the-foreland (D_1 or Caledonian) structures (Fossen, 1992, 1993a). There is now general consensus that the D_2 shearing reflects an extensional reactivation of the décollement zone, which has been explained by a change from contractional movements during plate convergence to divergent plate motions in the Devonian (Fossen and Rykkelid, 1992; Wilks and Chutbert, 1994; Milnes *et al.*, 1997; Rey *et al.*, 1997).

Extensional deformation is also expressed by large-scale west to northwesterly-dipping shear zones rooted in the ductile lower crust, particularly the Hardangerfjord shear zone (HSZ; Fossen, 1992), the Bergen Arc shear zone (BASZ; Fossen, 1992; Wennberg and Milnes, 1994; Wennberg, 1996), and the Nordfjord-Sogn detachment zone (NSDZ; Norton, 1987; Séranne and Séguret, 1987; Andersen and Osmundsen, 1994; see profiles in Fig. 1). These are NW- to W-dipping ductile shear zones with normal displacements on the order of a few kilometers or tens of kilometers (HSZ, BASZ) to more than 100 km (NSDZ: Norton, 1986). The NSDZ transects and offsets the entire orogenic wedge, and Devonian clastics deposited on its hanging wall are brought into close contact with the eclogite-facies gneisses of the Western Gneiss Region. To the south, the NSDZ bifurcates and is connected to the steeper BASZ, which follows the contact zone between the Bergen Arc System and the Western Gneiss Region (Fig. 1). The main part of the motion on these NW- to W-dipping shear zones must, for kinematic reasons, post-date the top-to-the-(W)NW shearing along the décollement zone under the orogenic wedge (Fossen, 1992). A schematic illustration of the kinematic history of the south Norway Caledonides is shown in Fig. 2.

PREVIOUS ISOTOPIC WORK

Sm/Nd and U/Pb dating and *P–T* estimates of eclogites in the WGR indicate a high-pressure metamorphic event at ~425 Ma, with metamorphic pressures of at least 18–20 kb and temperatures ranging from 600 to 700°C in the west (e.g. Griffin and Brueckner, 1980; Gebauer *et al.*, 1985; Griffin *et al.*, 1985). Although the average age of this event (425 Ma) is not very well constrained (most eclogites record Sm/Nd mineral and U/Pb zircon crystallization ages between 450 and 400 Ma), it is similar to the 432 ± 6 Ma Sm–Nd isochron age for the peak metamorphism in the northern part of the WGR obtained by Dallmeyer *et al.* (1992) (note that all errors in this article are quoted at the 2σ level unless otherwise noted).

Relatively few ^{40}Ar/^{39}Ar and K–Ar thermochronological studies have been carried out in the southern Norwegian Caledonides, except for the coastal areas (Fig. 3). The first ^{40}Ar/^{39}Ar analyses reported from the present study area were those of Strand (1969), who cited a biotite plateau age of about 417 Ma and a hornblende plateau age of 463 Ma from supracrustal rocks in the foreland (Grotli) of the thrust system (as much of the critical analytical information is undocu-

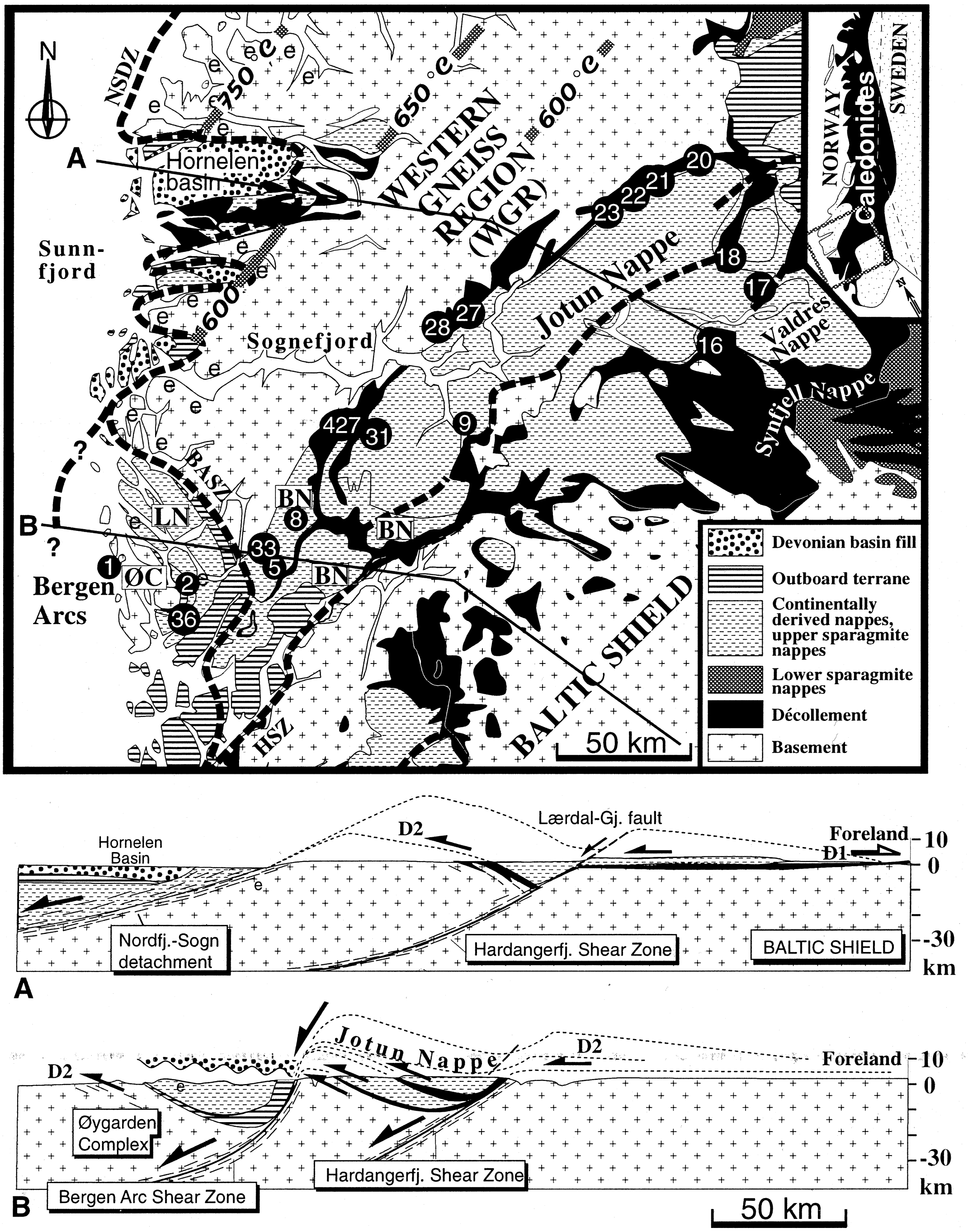
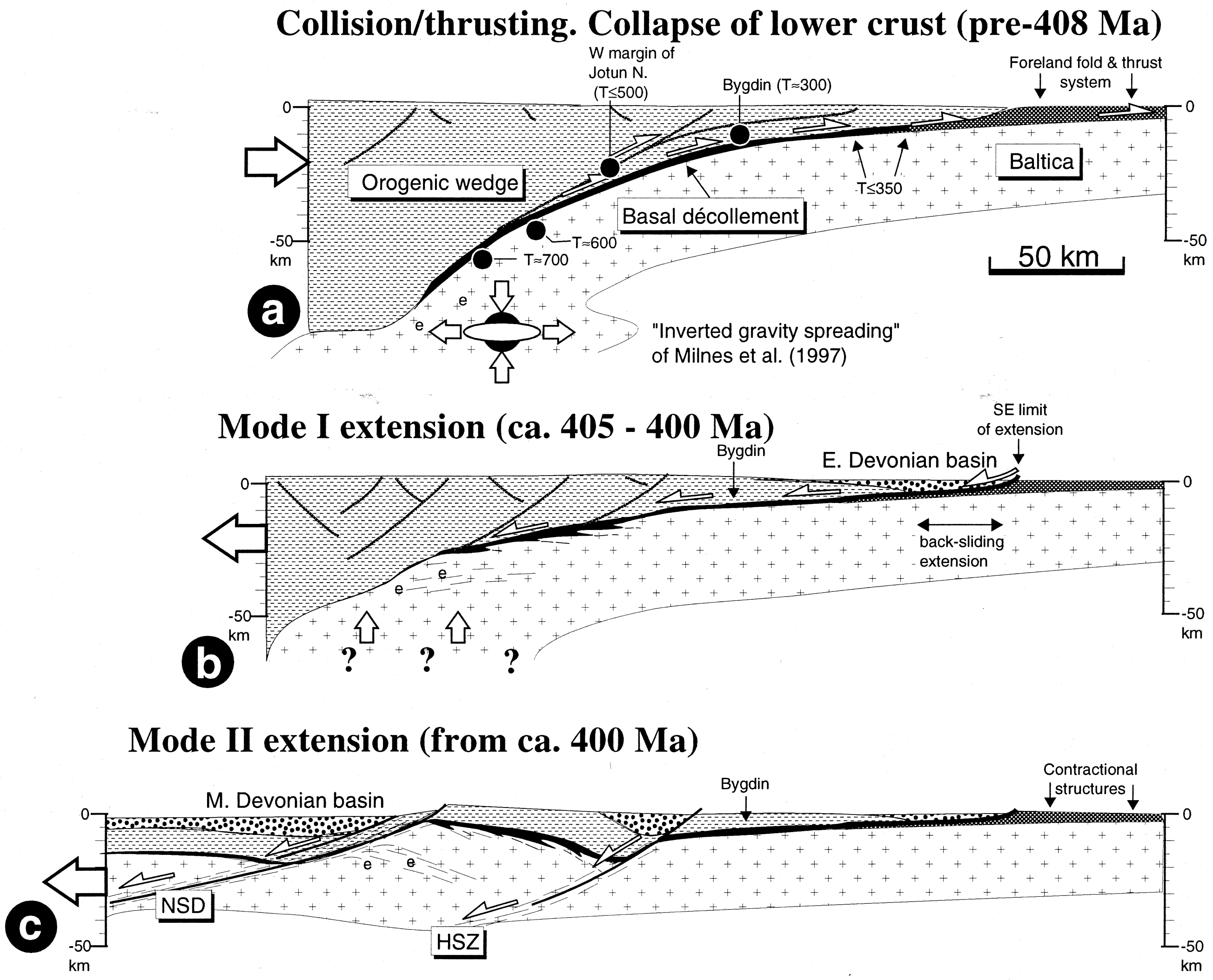


Fig. 1. Geological map, showing main tectonic units and sampling localities. Two profiles illustrate the large-scale overprint of the extensional deformation on the Caledonian nappe region. Temperature contours in the WGR are adapted from Griffin *et al.* (1985). D_1—thrusting/contractional deformation. D_2—extension-related deformation. BN—Bergsdalen Nappes, HSZ—Hardangerfjord shear zone, LN—Lindås Nappe, NSDZ—Nordfjord-Sogn detachment zone, ØC—Øygarden Complex, e—eclogites. After Fossen (1992).

mented, these data must be considered with caution). In addition, two biotites from the same area yielded K–Ar ages of about 383 ± 8 Ma (1σ) (recalculated using the decay constant of Steiger and Jaeger, 1977).

Bryhni *et al.* (1971) measured a ^{40}Ar/^{39}Ar plateau age of about 400 ± 2 Ma (1σ) for a biotite from the WGR east of the Hornelen basin (Fig. 1). An amphibole from the same area yielded Paleozoic (Cambrian) minimum ages, suggesting partial resetting during Caledonian tectonometamorphism. Farther west in the WGR (north of the Hornelen basin) Bryhni *et al.* (1971) determined a K/Ar age of 466 ± 9 Ma (1σ, recalculated) for one muscovite and a ^{40}Ar/^{39}Ar isochron age of about 488 ± 2 Ma (1σ) for a biotite, but the significance of these data is unclear.

More recently, Lux (1985) presented a comprehensive ^{40}Ar/^{39}Ar and K/Ar study of a restricted part of



Collision/thrusting. Collapse of lower crust (pre-408 Ma)

Mode I extension (ca. 405 - 400 Ma)

Mode II extension (from ca. 400 Ma)

Fig. 2. Silurian–Devonian development of the eastern (Scandinavian) side of the Caledonian collision zone. The orogenic wedge was overriding the subducted edge of Baltica at the time of continent–continent collision (a), and was shortly after affected by reversed movement (extension) along the basal décollement (b) and, eventually, by down-to-the-W shear zones (c). The new ^{40}Ar/^{39}Ar data indicate that the change from stage (a) to (b) occurred at about 408–402 Ma. Thermochronological modeling of K-feldspar indicates a maximum temperature near Bygdin at about 300°C, increasing to the west. See text for discussion.

the WGR in the coastal region north of the Hornelen basin and concluded that hornblendes cooled through about 500°C at ~410 Ma whereas biotites cooled through about 300°C at ~370 Ma. Chauvet and Dallmeyer (1992) performed an ^{40}Ar/^{39}Ar study of hornblendes and muscovite from the near-coastal region between the Hornelen basin and the Bergen Arcs (Fig. 1). They determined plateau ages for eight muscovite concentrates that range from 393 to 403 Ma, which they related to W-directed extensional shearing and unroofing of the footwall of the NSDZ. Several of the hornblende age spectra are markedly disturbed, yielding plateau-like minima between 490 and 421 Ma. These results suggest only partial resetting of older mineralogies during Caledonian metamorphism at these locations. A single muscovite from a gneissic rock much further east in the WGR and outside the NSDZ gave a plateau age of 442 ± 1 Ma.

Preliminary results from ^{40}Ar/^{39}Ar dating of continental rocks from the hanging wall of the NSDZ in Sunnfjord (Fig. 3) suggest cooling through muscovite closure temperature at about 446 Ma (Berry *et al.*, 1994). These older ages may represent early Caledonian cooling prior to the main continent–continent collisional stage, and contrast with younger ages within the NSDZ reported by the same authors (Berry *et al.*, 1995).

Boundy *et al.* (1996) presented ^{40}Ar/^{39}Ar data for hornblendes and muscovites from the Bergen Arc System and the immediately adjacent WGR. They report 450 Ma hornblende and ~430 Ma muscovites from partly eclogitized rocks in the Lindås Nappe

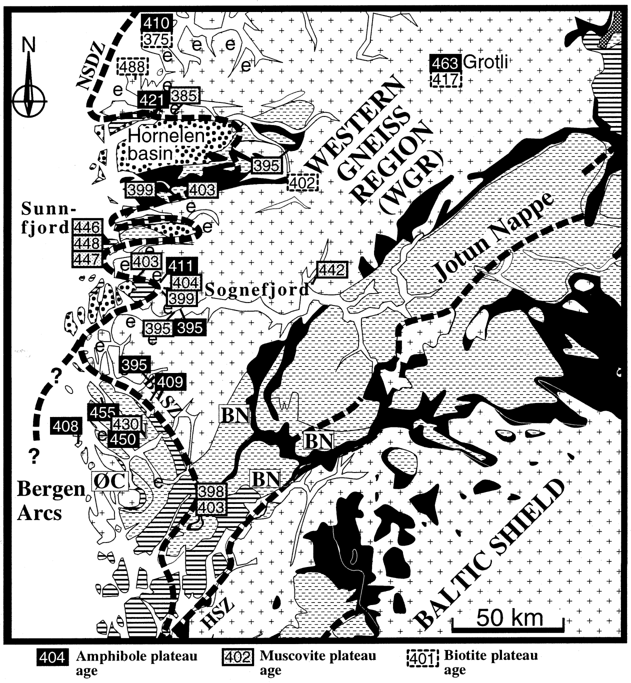


Fig. 3. Previous $^{40}Ar/^{39}Ar$ plateau ages in the study area (from Strand, 1969; Bryhni *et al.*, 1971; Lux, 1985; Chauvet and Dallmeyer, 1992; Boundy *et al.*, 1996; Fossen and Dallmeyer, 1998). The data are mainly restricted to the coastal area in the vicinity of the Nordfjord-Sogn Detachment Zone (NSDZ).

(LN, Fig. 1), whereas rocks to the east (WGR) and west (ØC in Fig. 1) of the nappe yield hornblende ages that are significantly younger (395–410 Ma).

TIMING OF OROGENIC EVENTS

Foreland region

The autochthonous to allochthonous sedimentary cover to the basement in southern Norway is preserved beneath and in front of the Jotun and similar crystalline nappes. Using the time scale by Gradstein and Ogg (1996), the youngest fossils in sediments overthrust by crystalline units are Llanvirnan (470–464 Ma) trilobites and graptolites (Bruton *et al.*, 1984; Nickelsen, 1985). Sediments younger than Llandvirn are only reported from the foreland sediments of the Oslo area, where increased rates of subsidence in middle Ordovician and Silurian times have been related to isostatic loading by advancing nappes (Bjølykke, 1983). The arrival of thrust nappes from the NW may also have caused an influx of sand in Llandeilian–Caradocian (464–449 Ma) beds near Mjøsa north of Oslo (Størmer, 1967), and particularly the uppermost Llandoverian (~430 Ma) Bruflat Sandstone (Bjørlykke, 1974). Similarly, post-early Ordovician turbidites in the Strondafjord and Gausdal Formations in the Synnfjell Nappe are interpreted as flysch in front of the advancing Jotun Nappe (Nystuen, 1981; Hossack *et al.*, 1985). The demonstrably youngest contractional deformation is recorded by open folding of the Ludlow and lower Pridoli (423–418 Ma) Ringerike Sandstone of the Oslo region (structurally beneath the Synfjell Nappe in Fig. 1; Bockelie and Nystuen, 1985).

Post-contractional sediments are absent in the foreland region, perhaps with the exception of Middle to Lower Devonian sediments in the hanging wall to an extensional shear zone in Røragen (NE of area covered by Fig. 1; Norton, 1987). Combined with the age of the Ringerike Sandstone, the change from contraction to extension thus appears to be of Lower Devonian age.

In conclusion, the present evidence indicates that the Jotun and other nappes were being thrust above Baltica toward the foreland in mid-Ordovician and Silurian times, and that thrusting in the foreland demonstrably continued until ~418 Ma and probably longer.

Hinterland

Exotic or outboard terranes along the coast of SW Norway contain fragments of mostly lowermost Ordovician ophiolites. These ophiolites contain numerous island-arc type intrusions as young as ~430 Ma (Fossen and Austrheim, 1988; marked as Rb/Sr in Fig. 4) and are covered by Late Ordovician to Early Silurian (~430 Ma) sediments (Thon, 1985), all of which pre-date the main (Silurian–Early Devonian) orogenic phase in West Norway. Furthermore, an obduction melange (Sunnfjord melange of Andersen *et al.*, 1990) overlies fossiliferous Wenlock (~425 Ma) sedimentary rocks of the Baltic margin in the hanging wall of the NSDZ, indicating that accretion of outboard terranes onto Baltica and the high-pressure metamorphism of the WGR may be broadly coeval.

Early Caledonian tectono-thermal events are well preserved in outboard terranes, but are also recorded in rocks of continental affinity, such as the continental margin-type Høyvik Group in Sunnfjord (Fig. 1; Brekke and Solberg, 1987). $^{40}Ar/^{39}Ar$ ages indicate unroofing of the Høyvik Group at about 450–435 Ma (Berry *et al.*, 1994), suggesting that the early Caledonian event was pre-Silurian in age. Other evidence that conforms to this interpretation include the $^{40}Ar/^{39}Ar$ amphibole plateau ages of 463 and 442 Ma reported by Strand (1969) and Chauvet and Dallmeyer (1992) from the WGR.

Devonian sediments (Steel *et al.*, 1985) post-date the Caledonian contraction in west Norway. The absolute age of these sediments is constrained by local occurrences of plant and fish fossils of Middle Devonian (391–370 Ma) age.

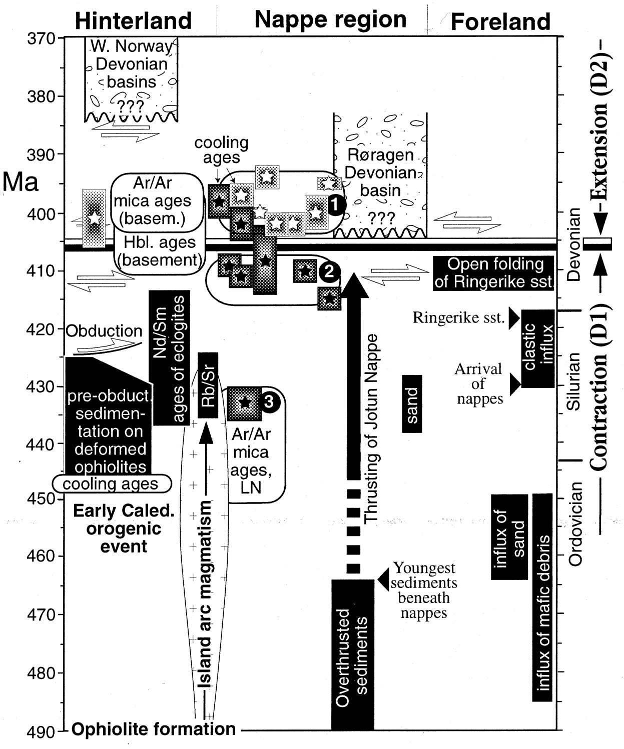


Fig. 4. Time scheme of the main evidence that help constrain the tectonic and kinematic evolution of the Caledonides. New mica plateau ages are plotted as stars with corresponding error boxes (2σ). The new ^{40}Ar/^{39}Ar data fall within two groups (boxes marked as 1 and 2), except for data from the Lindås Nappe (group 3), which coincides with older ages reported by Boundy *et al.* (1996). Size of box for group 3 and for data in the hinterland reflect the spread of data from previous work. Dark boxes: samples with D_1 (contractional) fabrics. Lighter boxes: samples exhibiting D_2 fabrics. The two D_1 samples in group 1 (B5 and M21) are explained by significant post-D_1 diffusive loss of argon in the western (high-T) part of the nappe region. Time scale of Gradstein and Ogg (1996). See text for more information.

SAMPLES AND RESULTS

In 1993, samples were collected for ^{40}Ar/^{39}Ar analysis along a 20 km east–west traverse through the Caledonian orogen in south Norway. The traverse starts in the sheared basement gneisses of the Øygarden Complex west of the Bergen Arcs, crosses the Bergen Arc System, the Bergsdalen Nappes and the décollement zone between the Jotun Nappe and the autochthonous basement and ends southeast of the Jotun Nappe in the Bygdin–Valdres area. The area that we have studied is relatively unknown from the viewpoint of K–Ar and ^{40}Ar/^{39}Ar thermochronology, with the exception of the works in the western parts by Boundy *et al.* (1996) and Fossen and Dallmeyer (1998).

The ^{40}Ar/^{39}Ar analytical data are collected in a separate table (available from the authors), and are presented as age spectra in Figs 5–7. A brief summary of these data, including calculated plateau ages, is compiled in Table 1, and the areal distribution of the plateau ages is shown in Fig. 8.

Øygarden Complex

The westernmost samples were collected from the Øygarden Complex (loc. 1 in Fig. 1), which is interpreted as Proterozoic basement rocks belonging to the Baltic Shield. This portion of the basement is strongly influenced by Caledonian deformation, and top-to-the-ESE fabrics are common in its eastern part toward the Bergen Arcs. However, the central, and in particular the western, portion of the Øygarden Complex is strongly overprinted by non-coaxial fabrics with a clear top-to-the-WNW sense of shear (Fossen and Rykkelid, 1990; Rykkelid and Fossen, 1992). The associated fabrics are similar to those found in basement gneisses within the NSDZ, and are related to the extensional (D_2) deformation of the Caledonides (Fossen, 1993b).

Biotite and amphibole concentrates (B1E and H1E in Table 1) were prepared for a sample of an amphibolite layer in mylonitic gneisses with clear top-to-the-WNW shear sense. The locality is identical to the Toftøy locality in Rykkelid and Fossen (1992). The amphibole concentrate yielded an age spectrum with a broad plateau-like character, but with ages ranging between 403 and 426 Ma (Fig. 5). Nevertheless, this sample does yield a pseudo-plateau age of 404 ± 1 Ma for the latter 52% of gas release. The age of the amphibole is similar to that reported by Boundy *et al.* (1996) from the same area. The biotite from the same sample gives a rising age spectrum that rapidly attains a plateau-like character, wherein ages range mostly between 398 and 403 Ma (Fig. 6). We take the age of

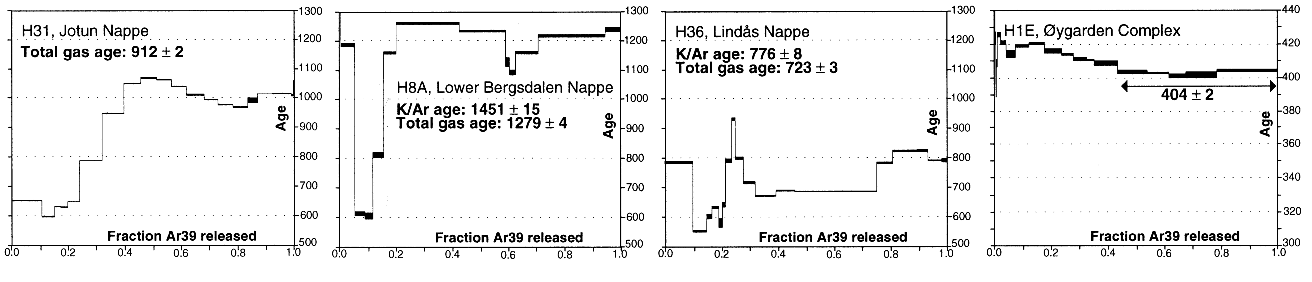


Fig. 5. ^{40}Ar/^{39}Ar apparent ages (release spectra) of amphibole concentrates from the study area. Experimental temperatures increase from left to right. Height of bars reflect 1σ uncertainties. For locations, see Fig. 1.

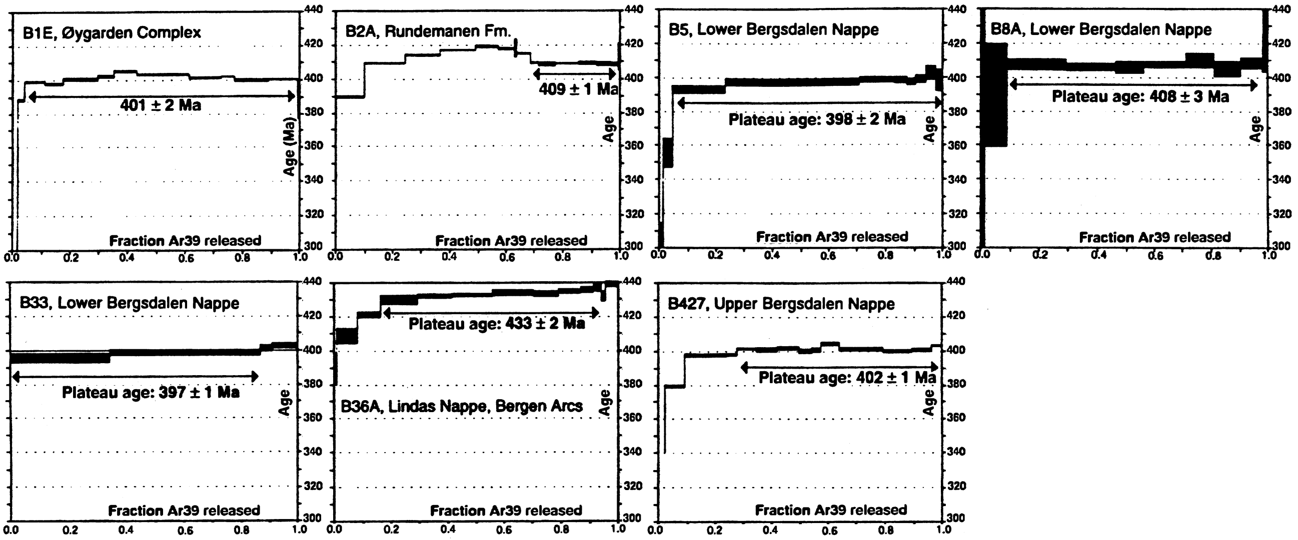


Fig. 6. ^{40}Ar/^{39}Ar apparent ages of biotite concentrates from the study area. Height of bars reflect 1σ uncertainties. For locations, see Fig. 1

this sample to be 401 ± 2 Ma, as a conservative estimate.

The Bergen Arcs

Amphibole concentrate H36, from a Proterozoic granulite-facies rock intruded by Precambrian granite dikes and sheared during the Caledonian thrusting, yields a K/Ar age of 776 ± 16 Ma (Table 2) and a disturbed ^{40}Ar/^{39}Ar release spectrum with a total gas age of 723 ± 5 Ma (Table 1), suggesting that the sample is heterogeneous in radiogenic (possible excess?) argon concentration. Although some Paleozoic age steps are realized (Fig. 5), the amphibole retains a Sveco-Norwegian (Grenvillan) signature that has been partially overprinted by the Caledonian tectonometa-

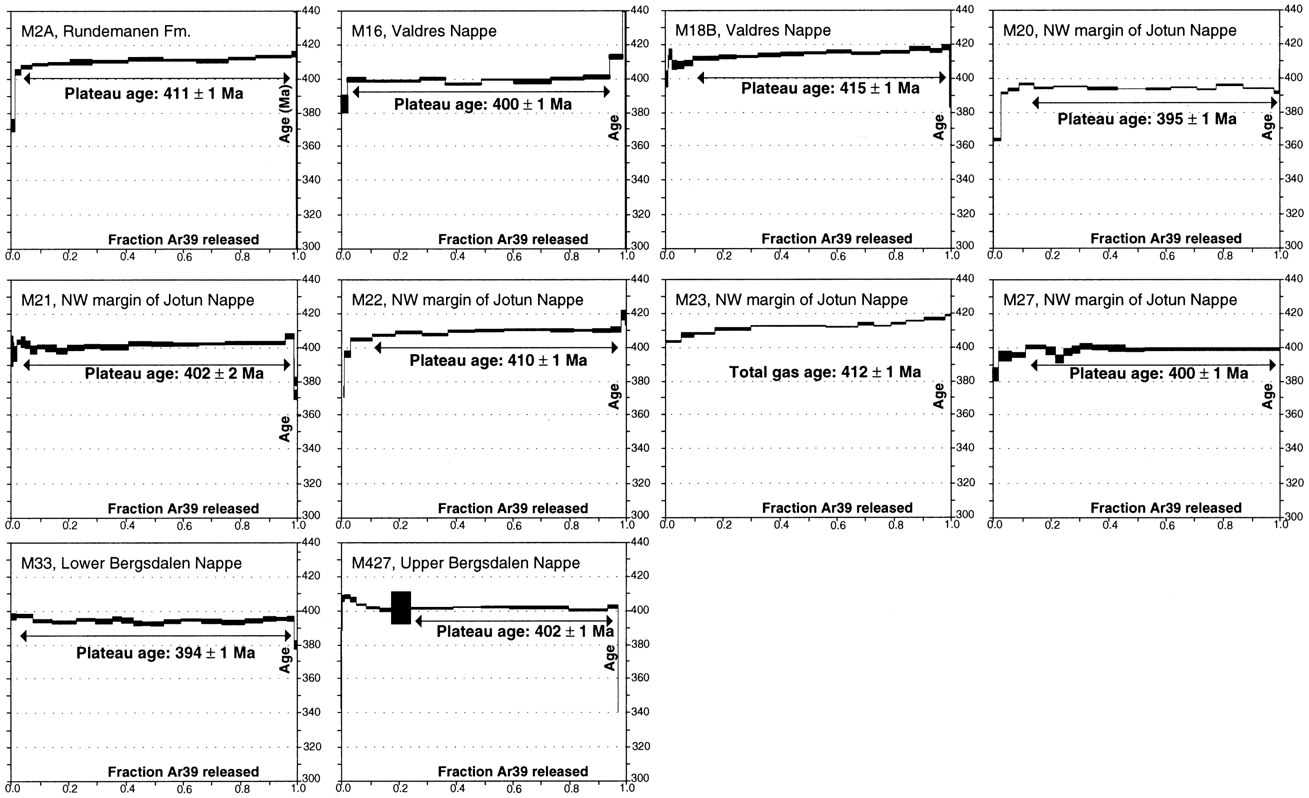


Fig. 7. ^{40}Ar/^{39}Ar apparent ages of muscovite concentrates from the study area. Height of bars reflect 1σ uncertainties. For locations, see Fig. 1.

Table 1. ^{40}Ar–^{39}Ar data

Sample	Unit	Kinematics, etc.	UTM	Total gas age (Ma)	Isochron age (Ma)	Isochron 40/36	Plateau age (Ma)
H1E	ØC	top-to-WNW (D_2)	KN767119	410 ± 2	na	na	(404 ± 1)
H8A	LBN	almost undeformed	LN457260	1279 ± 10	na	na	na
H31	JN	weak D_1 fabric	LN695635	912 ± 4	na	na	na
H36	LN	top-to-NE (D_1)	LM006893	723 ± 5	na	na	na
M2A	R.Fm	top-to-E (D_1)?	KN999037	410 ± 2	411 ± 1	289.9 ± 2.5	411 ± 2
M16	VN	top-to-NW (D_2)	MN901950	402 ± 2	*	*	400 ± 3
M18B	VN	top-to-SE (D_1)	NP020372	402 ± 2	*	*	415 ± 2
M20	DQ	na	MP710520	394 ± 2	*	*	395 ± 1
M21	VS	top-to-SE (D_1)	MP624414	402 ± 3	*	*	402 ± 3
M22	VS	D_1(?)	MP568373	409 ± 2	409 ± 1	297.6 ± 10.5	410 ± 2
M23	VS	D_1(?)	MP490285	412 ± 2	*	*	na
M27	DPh	top-to-W (D_2)	MP089073	400 ± 3	401 ± 1	284.9 ± 9.7	400 ± 1
M33	LBN	top-to-W (D_2)	LN337265	395 ± 2	394 ± 1	320.5 ± 31.7	394 ± 2
M427	UBN	top-to-WNW (D_2)	LN593612	398 ± 3	403 ± 1	289.9 ± 1.4	402 ± 2
B1E	ØC	top-to-WNW (D_2)	KN767119	379 ± 1	*	*	401 ± 5
B2A	R.Fm	top-to-E (D_1)?	KN999037	411 ± 2	*	*	(409 ± 2)
B5	LBN	top-to-E (D_1)	LN352177	395 ± 5	399 ± 1	282.5 ± 1.9	398 ± 3
B8A	LBN	weak D_1 fabric	LN457260	405 ± 16	408 ± 1	295.0 ± 1.9	408 ± 6
B33	LBN	top-to-W (D_2)	LN337265	395 ± 3	398 ± 1	289.0 ± 2.1	397 ± 2
B36A	LN	top-to-NE (D_1)	LM007892	430 ± 3	433 ± 1	271.0 ± 2.1	433 ± 3
B427	UBN	top-to-WSW (D_2)	LN593612	397 ± 2	*	*	402 ± 2

All ages are $\pm 2\sigma$. Samples (all 5–40 mg) are highly radiogenic such that 40/36 isochron intercepts are often controlled by only one or two data points. All isochron regressions are via the method of York (1969), and errors include MSWD. Isochrons include all measured steps, except for M427 where step 1 was excluded. Plateau ages are defined as the step size weighted mean age of contiguous steps comprising at least 60% of the gas, where the range of measured ages, and the error in the measured ages, is less than 1.5% of the weighted mean age. Abbreviations: H = amphibole sample, M = muscovite sample, B = biotite sample, ØC = Øygarden Complex, LBN = Lower Bergsdalen Nappe, UBN = Upper Bergsdalen Nappe, JN = Jotun Nappe, VN = Valdres Nappe, VS = Valdres sparagmite, R.Fm = Rundemanen Formation, DQ = Decollement quartzite, DPh = Decollement phyllite, D_1 = Thrusting, D_2 = Mode I extension, na = not applicable, * too radiogenic for isochron regression

morphism. Biotite B36A, from a sheared granitic dike within the granulite, exhibits a plateau age of 433 ± 3 Ma over 77% gas release, which is nearly identical in age to muscovites from the northern part of Lindås Nappe (Boundy *et al*., 1996).

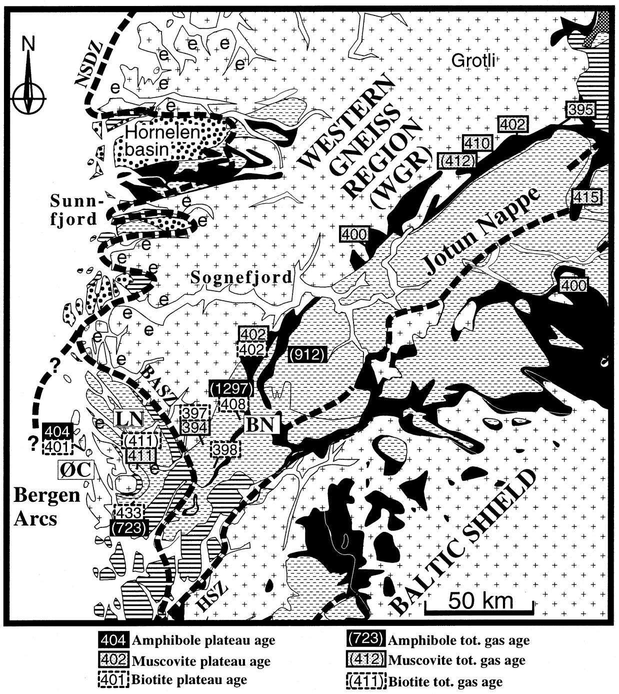


Fig. 8. Distribution of $^{40}Ar/^{39}Ar$ ages from the current study.

Psammitic metasedimentary rocks of post-Sveconorwegian and pre-Caledonian age (the Rundemanen Formation) are contained in greenshist-facies Caledonian shear zones in the Precambrian Ulriken Gneiss Complex and together constitute a small but distinct tectonic unit (Blåmanen Nappe) immediately west of and below the Lindå Nappe (Holst and Fossen, 1987; Fossen, 1988). Biotite and muscovite was concentrated from sample 2A from an extremely flattened and completely recrystallized quartzite conglomerate of the Rundemanen Formation. Biotite (B2) yielded a K/Ar age of 397 ± 9 Ma (Table 2) but no well-defined plateau is seen from the $^{40}Ar/^{39}Ar$ release spectrum (Fig. 6), which rises from 390 to 419 Ma, and 'plateaus' at 409 ± 2 Ma. Only one generation of mica is seen in thin section, suggesting the possible influence of excess argon on the shape of the age spectrum. However, isochron analysis does not confirm an excess component. The preferred age of the sample is about 409 Ma, taken from the plateau-like segment in the last 30% of gas release.

Muscovite from the sample (M2A) yields a plateau age of 411 ± 2 Ma (over 95% of gas release), suggesting complete rejuvenation of any detrital component at this time. In agreement with the B2A biotite spectrum, this result may indicate cooling through ~350°C (cf. Dunlap, 1997) for the Rundemanen Formation slightly earlier than the Øygarden Complex to the west and the Bergsdalen Nappes to the east (see below), or that the D_1 deformation and recrystalliza-

Table 2. K–Ar data

No.	ANU♯	Mineral	K wt%	Rad ^{40}Ar, 10^{-9} mol/g	100 × Rad ^{40}Ar Total ^{40}Ar	Age Ma ± 2σ
B2A	95257	Biot	7.746, 7.660	5.930	75.1	396.8 ± 8.8
H8A	95275	Hbd	0.2757, 0.2434	1.104	97.1	1451 ± 30.0
B9A	95260	Biot	7.270, 7.140	10.89	61.2	710.7 ± 18.2
K28	95261	Kspar	10.84, 10.73	9.007	73.1	426.8 ± 8.8
B33	95272	Biot	7.582, 7.676	6.014	96.0	405.4 ± 9.6
H36	95274	Hbd	0.9414, 0.9396	1.581	96.3	775.6 ± 16.0

Abbreviations are Biot, biotite; Hbd, hornblende, ANU♯, Australian National University catalogue number; K, potassium, Decay constants are $\lambda_e = 0.581 \times 10^{-10}/y$ and $\lambda_\beta = 4.962 \times 10^{-10}/y$. The K–Ar analytical methods follows those described in Dalrymple and Lanphere (1969)

tion of the Rundemanen Formation occurred at ~411 Ma (see below).

The Bergsdalen Nappes

The Bergsdalen Nappes occur east of the Bergen Arcs and structurally underneath the Jotun Nappe (Fig. 1). The nappes constitute two main tectonic units, the Upper and Lower Bergsdalen Nappes, which are very similar with respect to lithology and structural development (Kvale, 1948; Fossen, 1993b,c). Phyllites and micaschists belonging to the basal décollement zone occur beneath, between and above the nappes due to tectonic imbrication.

A major amphibole-bearing quartz intrusion within the Lower Bergsdalen Nappe was sampled where the Caledonian and later D_2 deformation was very weak or absent. The amphibole concentrate (H8A) yields a K/Ar age of 1451 ± 30 Ma and a total gas ^{40}Ar/^{39}Ar age of 1279 ± 10 Ma, suggesting that the sample is heterogeneous with respect to radiogenic argon concentration. Although no plateau is defined by the ^{40}Ar/^{39}Ar release spectrum for this amphibole, the oldest age steps would suggest that the quartz diorite intruded prior to ~1260 Ma. This conclusion is supported by Rb/Sr ages of 1274 and 953 Ma obtained from granitic intrusions in the lower Bergsdalen Nappe (Pringle *et al.*, 1975; Gray, 1978) which from field relations appears to be younger in age. In addition, the youngest age steps in the ^{40}Ar/^{39}Ar age spectrum attest to minor resetting during Caledonian orogenesis, and metamorphic temperatures not greatly exceeding 500°C for any extended period. Metamorphic biotite from the same sample (B8A) yields a well-defined plateau at 408 ± 6 Ma (covering 89% of gas release), indicating complete rejuvenation of the argon isotopic system in biotites at this time.

Sample 5 is from a sheared granitic body in the Lower Bergsdalen Nappe, the Bukkafjell Granite. Like other granites in the area, it contains a Caledonian foliation, and the sample shows a proto-mylonitic fabric and shear bands indicating top-to-the-E sense of shear. A metamorphic biotite (B5) from this sample displays a plateau age of 398 ± 3 Ma over 95% of gas release. The sample was collected from approximately the same locality where a Rb/Sr age of 953 ± 16 Ma has been obtained and interpreted as the age of intrusion (Pringle *et al.*, 1975).

The basal part of the Lower Bergsdalen Nappe is characterized by intense top-to-the-W D_2 fabrics. Muscovite concentrate M33, from a mylonitic gneiss within this zone, gives an excellent plateau at 394 ± 2 Ma for over 90% of gas release, whereas a biotite concentrate (B33) from the same rock gives an age spectrum that rises rapidly to a plateau at 397 ± 2 Ma covering 81% of gas release. Biotite from this sample gives a K/Ar age of 405 ± 10 Ma (Table 2) and a total gas ^{40}Ar/^{39}Ar age of 395 ± 3 Ma (Table 1). Four independent ^{40}Ar/^{39}Ar plateau ages from the Lower Bergsdalen Nappes and the overlying phyllonitic micaschist gave ages of 403–398 Ma (Fossen and Dallmeyer, 1998).

Muscovite and biotite samples M427 and B427 were concentrated from a quartz-schist from the Upper Bergsdalen Nappe. The sample contains shear bands that indicate a top-to-the-WNW sense of shear under greenschist-facies conditions. The muscovite yields apparent ages that descend to a plateau at 402 ± 2 Ma over 73% of gas release whereas the biotite exhibits a rising age spectrum that plateaus at 402 ± 2 Ma for over 72% of gas release.

Décollement zone (phyllite zone)

Two muscovite concentrates were prepared from samples collected from the phyllites under the Jotun Nappe. The westernmost sample (M27) is from a quartz-rich layer in the phyllite along the northwestern margin of the Jotun Nappe. The quartz-rich layer is interpreted as a part of the Cambrian (?) sedimentary cover to the Western Gneiss Region. A well-defined ^{40}Ar/^{39}Ar plateau age of 400 ± 1 Ma, covering 85% of gas release, was obtained for muscovite from locality 27. Farther northeast along the same contact, a similar quartzite was sampled (sample 20), and a plateau age of 395 ± 1 Ma was found (calculated for 86% of gas release). Both of these samples exhibit mylonitic fabrics with asymmetric structures clearly indicating top-to-the-NW sense of shear (D_2).

Samples of phyllites along the southeast side of the Jotun Nappe were too fine grained for pure micas to be concentrated.

Northwestern margin of the Jotun Nappe

Quartz-schists and meta-arkoses along the northwestern margin of the Jotun Nappe and above the phyllitic décollement are petrologically similar to those of the Valdres Nappe to the southeast (see below). These metasedimentary rocks contain mylonitic structures that indicate top-to-the-SE sense of shear, but on a larger scale these fabrics are folded by asymmetric, W-verging folds that are interpreted to be formed during top-to-the-NW (D_2) movements (Fossen and Holst, 1995).

Muscovites from three samples from these schists (21, 22 and 23) were concentrated. Muscovite M21 yields an excellent plateau at 402 ± 3 Ma over 92% of gas release, whereas muscovite M22 gives a rising age spectrum that plateaus for about 85% of gas release at a somewhat higher value of 410 ± 2 Ma. Muscovite M23 yields a rising age spectrum that does not define a plateau. Apparent ages range from 404 to 419 Ma, indicating that strong concentration gradients in radiogenic ^{40}Ar exist within individual grains and/or that the radiogenic ^{40}Ar concentration varies significantly from grain to grain.

Valdres Nappe

Two samples of the late Proterozoic 'sparagmites' from the southeastern side of the Jotun Nappe (the Valdres Nappe) were collected and analyzed. These 'sparagmites' of the Valdres Nappe were part of a pre-Caledonian sedimentary basin that was strongly involved in the Caledonian thrusting history (Bockelie and Nystuen, 1985). The sediments now occur as tectonic slices beneath and in front of the Jotun Nappe, but locally preserved primary contacts indicate that crystalline, Proterozoic rocks of the Jotun Nappe were originally part of the basement on which the 'sparagmites' were deposited (Schärer, 1980; Milnes and Koestler, 1985). Penetrative tectonic fabrics in the 'sparagmites' which are ascribed to the Caledonian thrusting history (Hossack, 1968a,b) were heterogeneously overprinted by the later D_2 (top-to-NW) fabrics (extension; Fossen, 1992). Two samples were collected from the Valdres nappe, one which exhibits evidence for a D_2 overprint (sample 16) and one which does not (sample 18B).

M18B, from a strongly foliated quartz-schist exhibiting a clear top-of-the-SE sense of shear, yields an age spectrum which rises in age from the fourth step at 408 ± 2 Ma to become plateau-like for almost 90% of gas release, defining an age of about 415 ± 2 Ma. It is possible that this sample contains multiple generations of muscovites that formed over a period of a few million years (cf. Dunlap, 1997). M16 comes from a quartz schist exhibiting top-to-the-NW sense of shear (opposite that of 18B) and yields a markedly younger plateau age of 400 ± 3 Ma.

Western Gneiss Region

A sample was collected from the Hafslo porphyry granite within the WGR (locality 28), near the northwestern margin of the Jotun Nappe. The K-feldspar in this sample has given a K–Ar age of 427 ± 9 Ma (K28 in Table 1), which is older than the majority of K–Ar and ^{40}Ar/^{39}Ar ages within the WGR. Similarly, a muscovite of Chauvet and Dallmeyer (1992) from nearby and also within the WGR also gave a relatively old Caledonian age (442 Ma), which opens the possibility of Late Ordovician to Early Silurian orogenic activity in the WGR.

K-FELDSPAR THERMOCHRONOLOGY

A granite gneiss, sample 17A, was collected from the southeastern margin of the Jotun Nappe for the purposes of performing an argon diffusion experiment on the K-feldspar, and inverting the diffusion information into a time–temperature history following the method of Lovera *et al.* (1989). The multi-diffusion domain method assumes that, in both the natural and laboratory situations, the loss or retention of radiogenic argon is from a number of noninteracting domains of variable length scale (and/or activation energy). For our purposes, a single activation energy and a slab geometry for argon diffusion is assumed, and a spectrum of model diffusion length scales is determined. The larger the spectrum of length scales within any given K-feldspar, the larger the closure window for argon diffusion will be (typically 150–350°C). The justification for the multi-domain procedure, outlined in detail by Lovera *et al.* (1993), is that K-feldspars commonly contain dramatic age gradients which cannot be modeled in terms of argon diffusion from a single domain.

Gneiss 17A contains a high-temperature fabric typical for the Proterozoic deformation of this part of the Jotun Nappe (Schärer, 1980), and there is no microscopic evidence to indicate that the K-feldspar has been physically or chemically modified subsequent to formation of the gneissic fabric. Thus, the K-feldspar in sample 17A might be expected to record thermal information related to Caledonian thrusting, if the rocks remained in the K-feldspar partial retention window for diffusive loss of argon (~150–350°C) during emplacement of the nappe.

The age spectrum derived from detailed step heating of 17A K-feldspar, shown in Fig. 9(a), does indeed suggest that the sample remained in the partial retention window for diffusive loss of argon during Caledonian orogenesis; apparent ages rising from ~260 Ma to ~1000 Ma are recorded. A multi-diffusion domain solution (Lovera *et al.*, 1989) has been calculated for the Arrhenius data, using the time, temperature and fraction of ^{39}Ar released during the course of

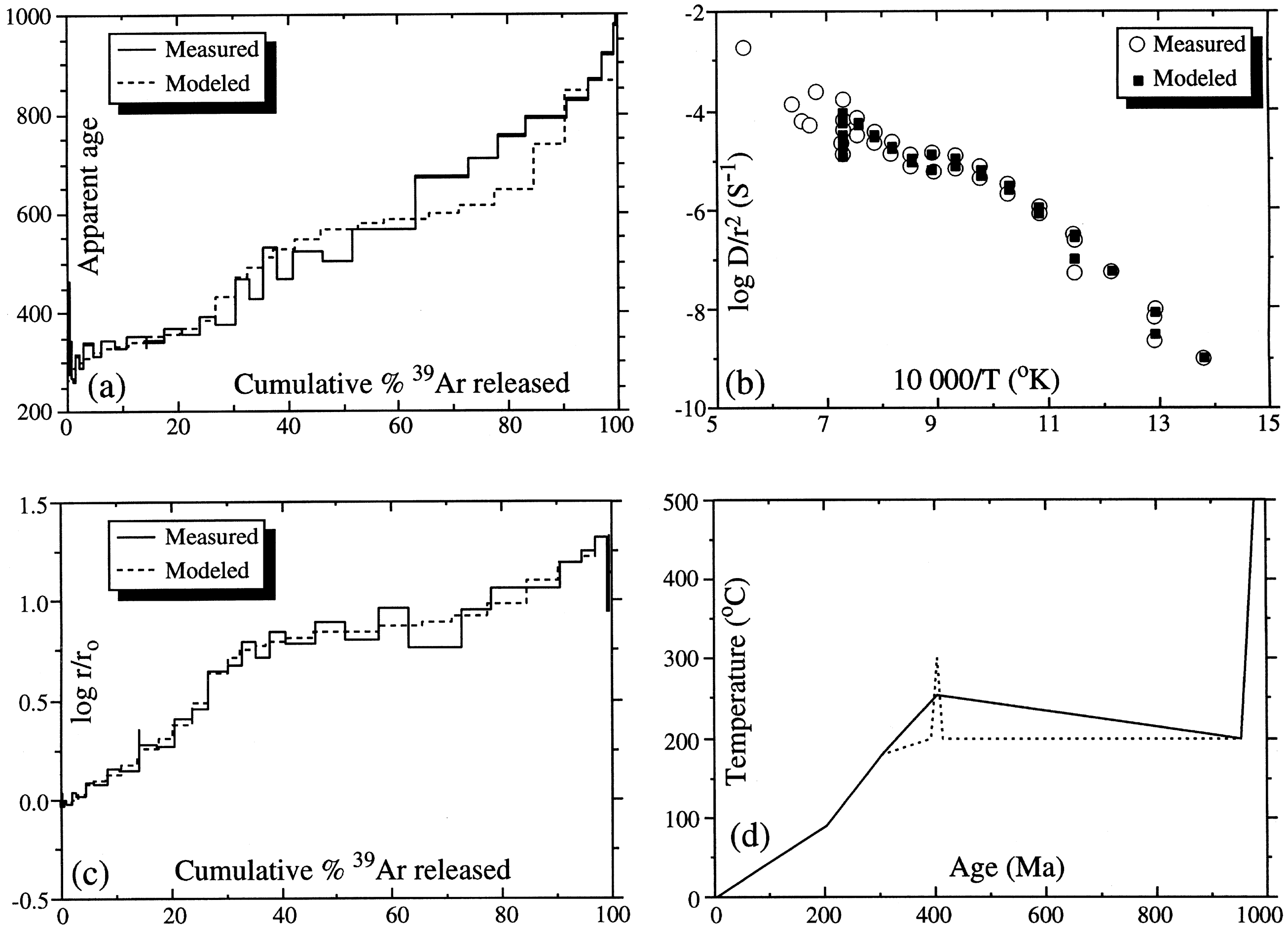


Fig. 9. Multi-diffusion domain analysis of sample 17A K-feldspar, basal part of Jotun Nappe near Bygdin: (a) age spectrum measured by step heating the sample in the laboratory (solid line) along with the best fit model age spectrum (dotted line), (b) Arrhenius plot for measured and modeled results, (c) log r/r_0 plot of both measured and modeled results, (d) end-member thermal histories which provide the best fit model age spectrum in (a).

the experiment. Both the measured and modeled results are shown in Fig. 9(b&c). The Arrhenius plot (Fig. 9b) shows that the mathematical solution, which incorporates six domains with an activation energy of 47 Kcal/mol and volume distribution (Table 3), provides a good fit of the laboratory degassing of ^{39}Ar.

The effective diffusion length scale for both the measured and modeled results, relative to that of a reference domain defined in the initial gas release, is plotted as log r/r_0 vs fraction of ^{39}Ar released in Fig. 9(c). During the course of the experiment the effective diffusion length scale changes by almost 1.5 orders of magnitude, due to progressive outgassing and complete exhaustion of gas from the smallest domains within the K-feldspar, such that by about 70% cumulative ^{39}Ar released (Fig. 9c) the effective length scale resolved is about an order of magnitude larger than that during the first few steps of the experiment.

The close fit between the measured and modeled results indicates that the theoretical domain distributions can be used to provide a synthetic model age spectrum that closely matches the one measured in the laboratory. This was done by input of trial thermal histories and minimizing the differences between the measured and modeled age spectra by manual iteration. It is assumed that the sample cooled from high temperatures (>500°C) in the Neoproterozoic (~900 Ma), but the model is not sensitive to this choice. A best fit model age spectrum is shown in Fig. 9(a). Thermal histories which produce the matching age spectra are shown in Fig. 9(d) (two near-end-member histories are shown). A thermal pulse around the time of the Caledonian orogeny is required, although the time span (i.e. wavelength) of the thermal pulse cannot be determined; the two time–temperature paths and all intermediate cases are indistinguishable. Sensitivity testing of the model indicates that the peak of reheating must occur between ~450 Ma and 350 Ma for a good fit to be obtained. In addition, the peak of reheating must be greater than about 250°C but less than about 300°C for a good fit to be obtained. In the case where the sample remained nearly isothermal subsequent to the Caledonian orogeny (dashed thermal

Table 3. Domain size distribution, 17A K-feldspar

Domain	log D_0 cm^2/s	Volume fraction	Domain size (relative)
17A K-feldspar, E_a = 46.9 Kcal/mol			
1	7.951	0.01174	0.00004
2	6.726	0.05420	0.00017
3	5.827	0.14637	0.00048
4	3.644	0.55895	0.00592
5	2.814	0.22210	0.01539
6	−0.812	0.00644	1.00000

history), an increase in cooling rate by about one order of magnitude is required at 285 + 10 Ma to fit the portion of the age spectrum from 0–25% gas release. Interestingly, this is the approximate timing of rifting in the Oslo Graben and probably also the North Sea (Neuman *et al.*, 1992).

INTERPRETATION

Most of the new ^{40}Ar/^{39}Ar plateau ages for micas from the nappe region in south Norway fall within two close but distinct age groups (Fig. 10). The youngest ages (group 1 in Fig. 4), which range from 402 ± 2 to 394 ± 2 Ma, were obtained from the décollement zone under the Jotun Nappe and the Bergsdalen Nappes. The biotite age from the western basement (Øygarden Complex) also falls within this group. A second group (group 2 in Fig. 4) of somewhat older (408 ± 6–415 ± 2 Ma) ages from similar rocks in the Jotun Nappe and Bergsdalen Nappe area correspond to the biotite and muscovite ages obtained from the Rundemanen Formation in the Bergen Arcs (~410 Ma; loc. 2). Only the biotite plateau age from the Lindås Nappe (Bergen Arcs) does not conform to this pattern, and, together with previously reported ages from the same nappe (Boundy *et al.*, 1996), define an older group (group 3 in Fig. 4). The significance of this grouping of ^{40}Ar/^{39}Ar ages will be discussed below.

In general, loss of radiogenic argon depends on the temperature history (maximum temperature and heating duration) and degree of recrystallization during deformation. White micas from intermediate pressure terranes are generally thought to have a closure temperature (Dodson, 1973) of about 350–400°C for cooling rates of a few tens of degrees per million years (Wagner *et al.*, 1977; Snee *et al.*, 1988; Hames and Bowring, 1994), whereas that for most amphiboles is probably about 500–550°C (Harrison, 1981; Baldwin *et al.*, 1990). The closure temperature for biotite is constrained to be slightly lower than that for white mica at about 300–350°C (Harrison *et al.*, 1985). If deformation occurred at temperatures well above the temperature of argon retention, the measured ages likely reflect the time since cooling through the closure temperature. If, on the other hand, deformation took place at lower temperatures, the measured ages may be influenced by deformation to the extent that the age of deformation itself is recorded (Dunlap *et al.*, 1991; Dunlap, 1997). Information of the temperature history is therefore of particular interest in the interpretation of the new ^{40}Ar/^{39}Ar ages from the south Norway Caledonides.

Increasing peak *PT*-conditions from SE to NW during Caledonian contraction is reflected by a change from middle greenschist mineral assemblages along the SE margin of the Jotun Nappe through uppermost greenschist/lowermost amphibolite facies in the Bergsdalen Nappes to amphibolite facies conditions in the NW (Øygarden Complex). *PT*-conditions were gradually lowered during the extensional history, first indicated by a decrease in grain-size and recrystallization of quartz and mica and, eventually, by overprinting of ductile by semi-brittle to brittle structures (e.g. Lærdal-Gjende fault; Milnes and Koestler, 1985; Fossen, 1998). It is generally possible to make qualitative and even semi-quantitative estimates of temperatures based on quartz microfabrics: significant dynamic or static recrystallization of quartz in quartzitic lithologies may indicate temperatures in excess of retention temperature of white mica and biotite (> 350°C), whereas deformed grains with much intracrystalline deformation structures and little recovery indicate the operation of mechanisms typical at temperatures around or slightly below the closure temperature of white mica (e.g. Brun and Choukroune, 1983; Hirth and Tullis, 1992; Passchier and Trouw, 1996; Dunlap, 1997).

In the eastern part of the study area, D_1 (thrusting) fabrics show evidence of strong recrystallization, with sub-polygonal, recrystallized quartz fabrics (Fig. 11c).

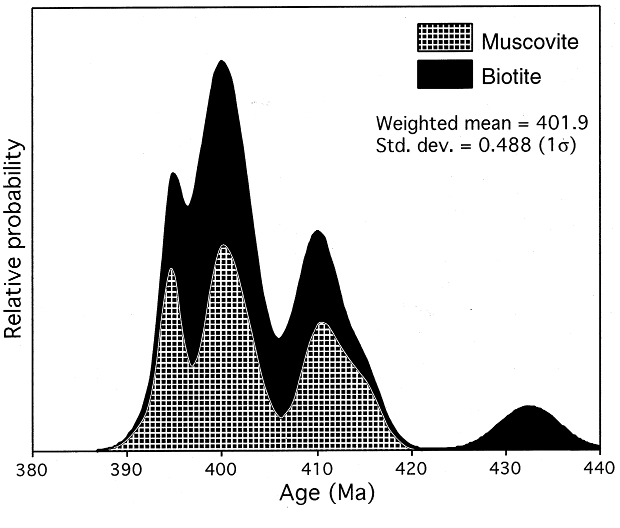


Fig. 10. Cumulative probability density plot of the mica plateau ages and associated errors listed in Table 1 (precision ≥ Ma, error involved = 2σ). The ~395–400 Ma peaks comprises ages interpreted as cooling ages in the west and ages of D_2 (extensional) shearing in the east, whereas the older (~410 Ma) peak is interpreted as the age of thrusting. See text for discussion, and see Silverman (1986) for details of calculation of probability distribution.

In contrast, D_2 fabrics are finer grained and poorly recovered (Fig. 11a&b). This difference is taken to indicate reduction in temperature during the D_2 top-to-the-NW shearing (Mode I extension), and that temperature may have been around or slightly below the closure temperature of white mica during Mode I extension. Grain size reduction could also be caused by increased stress (Twiss, 1977), but the temperature decrease demonstrated by $^{40}Ar/^{39}Ar$ cooling ages to the west at this time (~400 Ma) leads us to consider temperature as the main grain size controlling factor.

Nickelsen *et al.* (1985) used conodonts from a Ceratopyge limestone immediately beneath the Valdres Nappe (Fig. 1) on the SE side of the Jotun Nappe to estimate maximum Caledonian temperatures of 300–400°C, i.e. around the closure temperatures of micas. Additional information about the thermal history of the Jotun/Valdres nappes is now provided by the K-feldspar diffusion experiments of sample 17A, as reported above. The modeling shows that the present eastern margin of the Jotun Nappe was heated to a maximum Paleozoic temperature at ~400 ± 50 Ma and that the temperature did not exceed 300°C (Fig. 9). This temperature is slightly lower than the closure temperature of white mica (~350°C, as stated above). Therefore, micas in this part of the Jotun Nappe that crystallized during the Caledonian deformation may have been effectively closed to diffusive loss of argon since the time of their formation. If this is correct then the plateau ages are in fact ages of crystallization.

In the light of these results, there is a strong possibility that the two separate groups of well-defined plateau ages represent crystallization ages rather than cooling ages. Considering the fact that the samples are collected from a décollement zone with two kinematically, temporally and thermally different tectono-metamorphic events (D_1 and D_2), it is tempting to interpret the older ages as D_1 (thrusting) ages, and the younger ones as related to the extensional Mode I event (D_2). If we consider the ages of muscovites sampled at the base of, or immediately beneath, the Jotun Nappe it is clear that *all* the samples that exhibit unambiguous D_2 fabrics have mica ages between 395 and 402 Ma. Older ages (408–415 Ma) are *only* obtained from samples with well-preserved D_1 fabrics, although sample M21 from the NW margin of the Jotun Nappe with apparent top-to-SE (D_1) fabrics also yielded a young age (402 ± 3; Table 1). The most likely explanation for the young apparent age of M21 is that diffusive loss of argon was significant until ~402 Ma, even though the

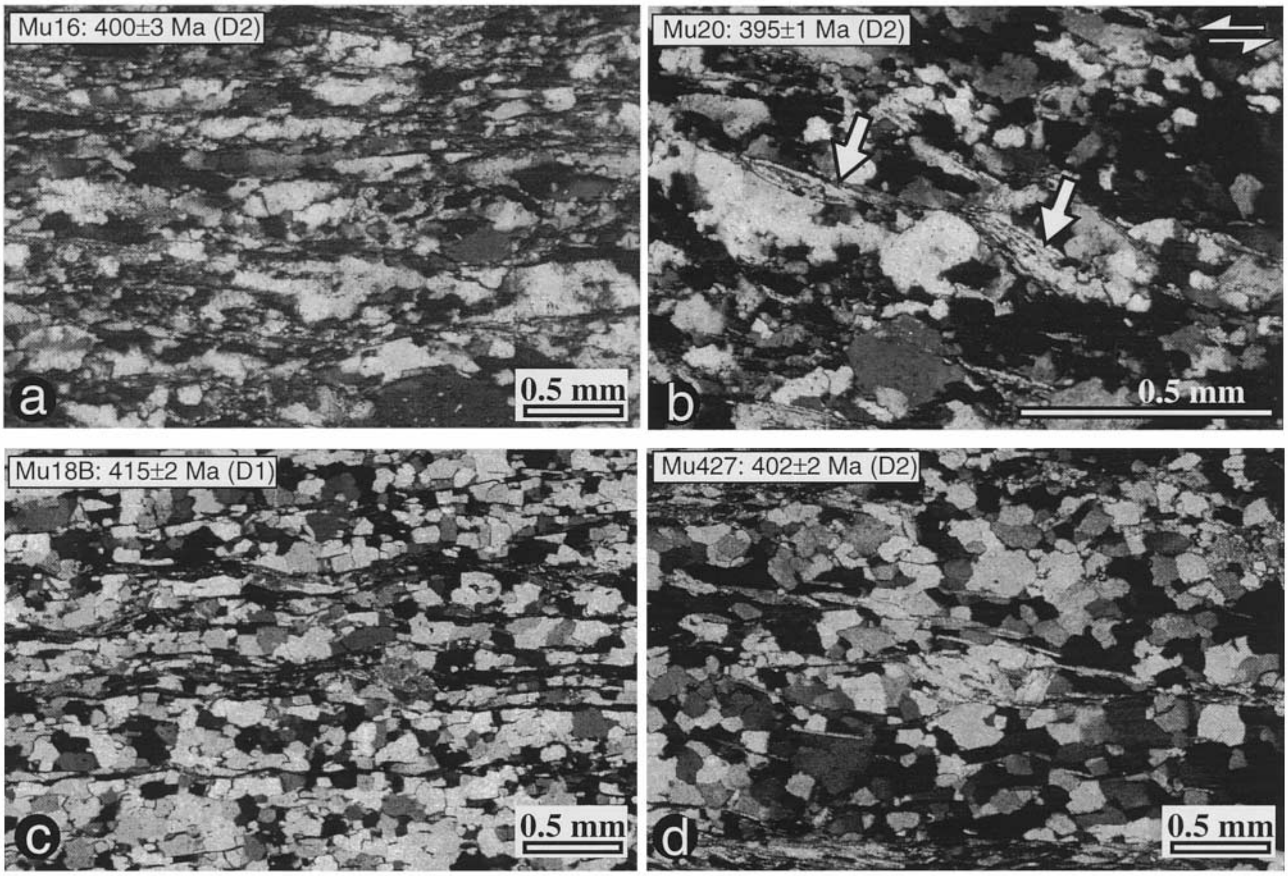


Fig. 11. Microphotographs of thin-sections of samples 16, 18, 20, and 427 (see Fig. 1 for location), (a), (c) and (d) are all of the same magnification. Sample 16 and 20 are strongly influenced by low- T D_2 deformation (mode I extension), and quartz is considerably less recovered than the higher-T D_1 fabric of sample 18 and the D_2 fabric of sample 427. $^{40}Ar/^{39}Ar$ ages of the latter samples (c & d) are interpreted as cooling ages, whereas those in (a&b) are more likely to be ages of D_2 deformation. Arrows indicate locations of white mica.

fabric of the rock is preserved from the earlier top-to-the-SE deformation. Furthermore, samples with D_1 fabrics are generally more recovered than those deformed during D_2 (Fig. 11). These observations lead us to conclude that in the eastern part of the nappe region, the group of 402–394 Ma ages indicate the age of ductile extensional deformation (D_2 shearing), whereas the 408–415 Ma ages are related to thrusting of the nappes to the SE.

In the Bergsdalen Nappes all samples with strong deformation fabrics (samples B5, M33, B33 and M427) show micro-textural evidence of recrystallization (recovery) during or after deformation (Fig. 11d). Coarse-grained blastomylonitic fabrics characterize these nappes, and fabrics in samples with top-to-the-E and top-to-the-W sense-of-shear indicators are generally indistinguishable except with respect to symmetry, indicating relative high ($>400°C$) temperatures throughout both D_1 and the Mode I extension (D_2). This interpretation explains why samples with both D_1 (sample B5) and D_2 fabrics (samples M33, B33 and M427) give similar ages in this part of the study area, as opposed to the eastern nappe region discussed above. We therefore interpret the 394–402 Ma ages in the Bergsdalen Nappes as the time of cooling through ~350°C during the post-contractional extension.

The temperature estimate of ~650–700°C calculated by Boundy *et al.* (1996) and the $^{40}Ar/^{39}Ar$ age difference between amphibole (H1E) reported in this study indicate that the ages from the Øygarden Complex should be regarded as cooling ages. The $^{40}Ar/^{39}Ar$ data thus record cooling through ~500°C at around 404 Ma (amphiboles) and through ~300°C at about 400 Ma (biotite), i.e. very rapid cooling simultaneous with cooling of the Bergsdalen Nappes and during or immediately following Mode I extension in the Jotun Nappe area. Because the sampled amphibolite facies mineral parageneses were stable during the first stage of top-to-the-WNW mylonitization in the Øygarden Complex (Fossen and Rykkelid, 1990; Rykkelid and Fossen, 1992), this mylonitization likely started before the 404–401 Ma cooling ages, although not necessarily much before.

The biotite and muscovite ages from the Blåmanen Nappe (Rundemanen Formation) near Bergen (locality 2) both gave ages that correspond to the second group (408–415 Ma) in Fig. 4. Combined with the fact that the sample has suffered contractional deformation only (top-to-the-E shearing), it is suspected that this age is directly related to the greenschist-facies contractional deformation.

In contrast to the Blåmanen Nappe, the 430 Ma plateau age of biotite from an amphibolite-facies Caledonian shear zone in the neighboring Lindås Nappe supports the interpretation of Boundy *et al.* (1996) that the temperature history of this unit differs from that of the Baltic basement and, as shown above, also from that of the Blåmanen, Jotun and Bergsdalen Nappes. The Lindås Nappe cooled through ~350°C at 430 Ma, and was maintained at a relatively low temperature throughout the rest of Caledonian orogeny and later extension. Boundy *et al.* (1996) estimate temperatures of 600–700°C and report amphibole ages of ~450 Ma from Caledonian eclogite-facies shear zones in the northern part of this nappe, whereas in the present contribution, we recognize that an amphibole concentrate from the south was only partly reequilibrated during the Caledonian tectonometamorphism (H36 in Fig. 5). The reason for this may be a combination of lateral variations in temperature, flux of fluids and/or other parameters during maximum Caledonian heating of the Lindås Nappe. The pre-Silurian cooling ages reported from outboard terranes near the Devonian basins (Berry *et al.*, 1994) suggest outboard orogenic activity prior to the continent–continent collision in the Silurian. It seems likely that the Lindås Nappe was involved in this Ordovician activity, either as a microcontinent or as part of the leading edge of Baltica. It is interesting that the mica age reported by Chauvet and Dallmeyer (1992) from the eastern part of the WGR (442 ± 1 Ma) falls within the oldest group (group 3 in Fig. 4) of $^{40}Ar/^{39}Ar$ ages, which, supported by the amphibole cooling age of Strand (1969; ~463 Ma), indicates an influence of Ordovician orogenic activity on the western portion of Baltica (WGR).

CONCLUSIONS

$^{40}Ar/^{39}Ar$ ages presented in this and previous reports define three groups of ages that may reflect fundamentally different tectonometamorphic events (Fig. 4). The oldest ages (450–430 Ma; Boundy *et al.*, 1996; this work) are found in high tectonic units such as the Lindås Nappe, and correspond with ages reported from outboard terranes and reworked basement of the Western Gneiss Region (away from the NSDZ). These ages are interpreted as the time of cooling after early Caledonian orogenic activity that involved continental as well as oceanic crust. The (contractional) deformation of the Lindås Nappe is thus likely to be older than the D_1 deformation at the base of the orogenic wedge to the east.

The intermediate group of ages (415–408 Ma; this work) were obtained in the eastern nappe region or in the higher Blåmanen Nappe in the west, and exclusively in rocks with contractional and microtexturally equilibrated fabrics. These ages likely reflect late stages of Caledonian thrusting of the Jotun Nappe and other allochthonous units. Two $^{40}Ar/^{39}Ar$ muscovite cooling ages from the NSDZ (415 and 416 Ma; Berry *et al.*, 1995) may possibly indicate that cooling and extension already took place in the hinterland by a gravity driven collapse mechanism, contemporaneous with general thrusting toward the foreland (Fig. 2a). Such a model has been assumed by Andersen *et al.* (1991) and included as a pre-divergent stage in the model by Fossen (1992, 1993a). However, most ages in the NSDZ (Chauvet and Dallmeyer, 1992; Berry *et al*., 1995) as well as in the present study area fall in the range of 402–394 Ma (youngest group of ages), which in the eastern nappe region is thought to be the age of Mode I extension (top-to-the-NW transport). In the west, however, temperatures were generally higher during initial stages of the extensional history, and most of the 402–394 Ma mineral ages in this region (cf. Chauvet and Dallmeyer, 1992) must represent cooling ages related to rapid exhumation during extension. No significant lateral differences are found within the youngest group of ages, indicating that uplift through the closure temperature of white mica and biotite in the west occurred simultaneously with the Mode I extension and/or during early stages of the immediately following Mode II extension (Fig. 2). The youngest (402–394 Ma) group $^{40}Ar/^{39}Ar$ ages obtained in this work (and by Fossen and Dallmeyer, 1998) represents a maximum age for the late stage of Mode II extension, when ductile structures started to be overprinted by brittle deformation.

The closeness between the two groups of $^{40}Ar/^{39}Ar$ ages suggests a very rapid change from a large-scale contractional to extensional setting at around 408–402 Ma (Lower Devonian). As illustrated in Fig. 4, $^{40}Ar/^{39}Ar$ dating of late stages of contraction or thrusting to 415–408 Ma and the following extension to 402–394 Ma fits very nicely with existing stratigraphic and radiometric data, and puts closer constraints on the timing of these events. In particular, there is time for both the contractional history in the hinterland and the thick-skinned thrusting in the foreland to be completed by the time the regional-scale extensional deformation started.

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APPENDIX

Analytical procedures for ^{40}Ar/^{39}Ar analysis of samples measured at the Australian National University are summarized by Dunlap *et al.* (1995), whereas that for samples analyzed at the University of California, Los Angeles (samples B1E, H1E, M427 and 17A K-feldspar) is outlined in Dunlap (1997).

Temperature was progressively increased over the course of step-heating experiments and was monitored by a thermocouple at the base of a tantalum crucible within a double vacuum resistance furnace. Experiments were started at or above 400°C and concluded at 1450–1500°C with the temperature held at each temperature step for a variable amount of time depending on the desired yield. The yields of various isotopes are listed in a separate table (available from authors upon request). At each extraction temperature, the gas released was exposed to Zr–Al getter pumps to remove active gases, and the argon was subsequently isotopically analyzed using gas source mass-spectrometers operated in the static mode (VG1200 and VG3600).

Measurements performed with the VG3600 of UCLA utilized both a Daly photomultiplier and a Faraday cup (Ar sensitivity of 2×10^{15} mol/mV). The typical gain of the photomultiplier was about 110. Mass discrimination varied within narrow limits and was measured periodically through analysis of air argon aliguots. Measurements performed on the VG1200 made use of an electron multiplier (Ar sensitivity of about 5×10^{17} mol/mV). Getter section blanks were normally below 5×10^{16} mol on mass 40 for static collection over 10 min. Blanks were essentially atmospheric as well as could be determined, and the mass 39 blank (10 min) was normally below 2×10^{18} mol. Furnace blanks below 1000°C were generally well below 5×10^{15} mol of ^{40}Ar.

Correction factors were determined from K_2SO_4, CaF_2 and synthetic K-glass included with the samples during irradiation, and the J factors were determined from Fish Canyon Sanidine (27.8 Ma; Cebula *et al.*, 1985) or GAISSO biotite (97.9 Ma; McDougall and Roksandic, 1974) by interpolative curve fitting. The ^{40}K abundance and decay constants recommended by the IUGS Subcommission on Geochronology were used (Steiger and Jager, 1977).

The samples, thin sections, and a detailed analytical table are included in the scientific collections at Bergen Museum, University of Bergen and may be borrowed by contacting the first author or Bergen Museum. Also, more detailed analythical data (tables) can be obtained for either of the authors.