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$^{40}Ar/^{39}Ar$ muscovite dates from the nappe region of southwestern Norway: dating extensional deformation in the Scandinavian Caledonides

Haakon Fossen [a,*], R.D. Dallmeyer [b]

[a] *University of Bergen, Department of Geology, Allegt. 41, N-5007 Bergen, Norway*
[b] *University of Georgia, Department of Geology, Athens, GA 30602, USA*

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Abstract

The Caledonian thrust nappes and basal décollement zone above the Baltic shield record penetrative Caledonian deformation related to ESE-directed nappe transport, and subsequent WNW-directed ductile shearing during extensional collapse of the orogen. Muscovite within Proterozoic quartzite conglomerates in the Lower Bergsdalen Nappe that record only ESE-vergent Caledonian deformation display internally concordant $^{40}Ar/^{39}Ar$ age spectra which yield plateau ages of 403 Ma and 398 Ma. Similar plateau ages (402 and 399 Ma) were obtained from muscovite from mica schists which record additional penetrative WNW-directed shearing, suggesting that muscovite intracrystalline argon systems did not cool below appropriate closure temperatures until during or after extensional WNW-vergent movements. Quartz microfabrics indicate that temperatures were higher than those required for argon retention in muscovite until the end of the WNW-directed nappe translation (extension), and that lower temperatures were maintained during subsequent movements along W- and NW-dipping extensional ductile shear zones. The $^{40}Ar/^{39}Ar$ muscovite ages are therefore interpreted to post-date the extensional WNW-directed shearing along the décollement zone, and closely date the initiation of W- and NW-dipping extensional shear zones. When compared to the age of contractional deformation, the results confirm that extension followed orogenic contraction very shortly after the main, Scandian orogenic phase.

Keywords: geochronology; tectonics; Caledonides; extension; Norway

1. Introduction

Application of kinematic analyses to deformation zones in ancient and active orogens has revealed a surprisingly large amount of extensional deformation zones that were regarded as compressional some 10–20 years ago (e.g., Coney and Harms, 1984; Holdsworth, 1989; Malavieille, 1993; Lynch and Tremblay, 1994; Constenius, 1996; Wallis and Behrmann, 1996). Both syn- and post-contractional extension structures occur, and the timing of the change from overall contractional to extensional tectonics is of particular interest. To approach such problems, structural/kinematic data must be combined with paleontological and/or geochronological data.

In the Caledonides of southern Norway, significant post-contractional extension has been identi-

* Corresponding author. Fax: +47 (55) 589416; E-mail: haakon.fossen@geol.uib.no

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fied as reactivation of the basal thrust zone (décollement) (Fossen, 1992; Fossen and Holst, 1995; Milnes et al., 1997) and, subsequently, by hinterland-dipping extensional shear zones (Norton, 1986, 1987; Séranne and Séguret, 1987; Andersen et al., 1991; Fossen, 1992; Wennberg and Milnes, 1994; Wilks and Cuthbert, 1994). While the kinematic and structural framework of the southern Norwegian Caledonides is now known in great detail, absolute time constraints are needed to understand the late and post-Caledonian evolution (Fossen, 1993a). As a contribution in this regard, we present here new $^{40}Ar/^{39}Ar$ mineral dates for nappe units exposed east of the Bergen Arcs.

2. Regional setting

The Caledonides in southern Norway (Figs. 1 and 2) constitute remnants of thrust nappes that were transported to the east-southeast above a Precambrian basement (Baltica) during Paleozoic convergence between Baltica and Laurentia. The Caledonian orogeny is interpreted to have culminated in a continent–continent collision, generally similar to the present-day Himalayas when the western edge of Baltica (Western Gneiss Region) was subducted beneath the Laurentian plate. This interpretation is supported by a P/T gradient which reflects very high pressures and temperatures (eclogite-facies) in western portions of the basement at ca. 425 Ma (Griffin and Brueckner, 1980; Griffin et al., 1985).

The upper thrust-nappes (Upper Allochthon) consist of exotic or outboard terranes that include fragments of ophiolitic and island arc complexes, some of which may have formed on the Laurentian side of the pre-collisional ocean (Pedersen et al., 1988). Lower nappes (e.g., the Jotun Nappe Complex) are dominated by Precambrian continental crust that was structurally detached from the hinterland of the orogen. A sequence of mostly pelitic rocks (predominantly phyllites and mica schists) of latest Proterozoic to Ordovician age covers the basement, and acted as a mechanically weak décollement during thrusting of the overlying nappes. Structural units of Precambrian crystalline rocks and/or their Late Precambrian sedimentary ‘cover’ were detached from the basement and incorporated into the décollement zone. The Bergsdalen Nappes, which are tectonically enveloped by phyllitic rocks or mica schists and sandwiched between the basement and the overlying Jotun Nappe Complex, represent two such tectonic levels.

The Nordfjord–Sogn Detachment Zone (NSDZ) and the Bergen Arc Shear Zone (BASZ) also represent important deformation zones in this area. The NSDZ is a zone of non-coaxially deformed lower Paleozoic and Precambrian crystalline rocks that structurally underlie Devonian basins north of the Bergen Arcs. This zone has been studied by various authors (e.g., Norton, 1987; Séranne and Séguret, 1987; Andersen et al., 1991; Andersen and Osmundsen, 1994), who have described intense top-to-the-W(NW) shearing related to extensional deformation. The BASZ is connected to the NSDZ, which appears to bifurcate south of Sognefjorden (Fig. 1). Further south, the Hardangerfjord Shear Zone (HSZ; Fossen, 1992) is a related structure that was active as an extensional shear zone following the Caledonian collisional history. Displacement along these shear zones varies from a few kilometers (HSZ) to several tens of kilometers (NSDZ).

2.1. Kinematics

Foreland-directed nappe movements in southern Norway have been estimated to be as much as several hundreds of kilometers (e.g., the Jotun Nappe Complex; Hossack and Cooper, 1986). However, detailed kinematic analysis of fabrics in the décollement zone has revealed that the dominant sense of shear was top-to-the-hinterland (Fossen and Rykkelid, 1992), implying significant WNW-directed translation of the orogenic wedge. Associated fabric elements overprint and locally obliterate fabrics related to top-to-the-foreland (SE) sense of shear (Fossen, 1992). There is now general consensus that the hinterland-directed shearing reflects an extensional reactivation of the décollement zone, and has been explained by a change from contractional movements during plate convergence to divergent plate motions in the Early Devonian (Fossen and Rykkelid, 1992; Fossen, 1993a; Wilks and Cuthbert, 1994; Rey et al., 1997). Extensional deformation is also recorded in large-scale, west- to northwest-dipping ductile to brittle shear zones. These shear zones include the HSZ (Fossen, 1992), the BASZ (Fossen,

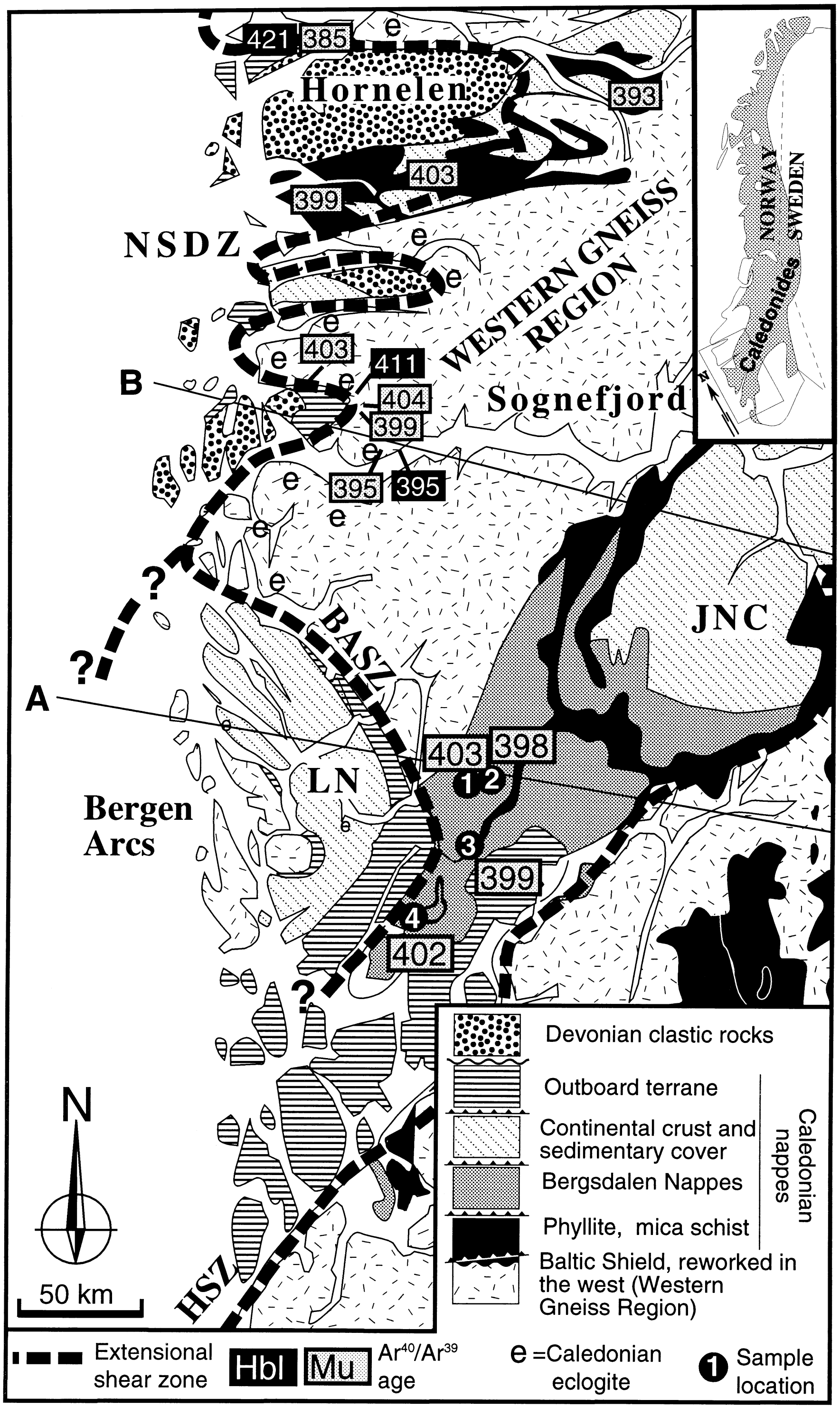

Fig. 1. Geological map of southwestern Norway. *NSDZ* = Nordfjord–Sogn Detachment Zone; *BASZ* = Bergen Arc Shear Zone; *HFSZ* = Hardangerfjord Shear Zone; *LN* = Lindås Nappe; *JNC* = Jotun Nappe Complex. Ages north of Sognefjord are from Chauvet and Dallmeyer (1992).

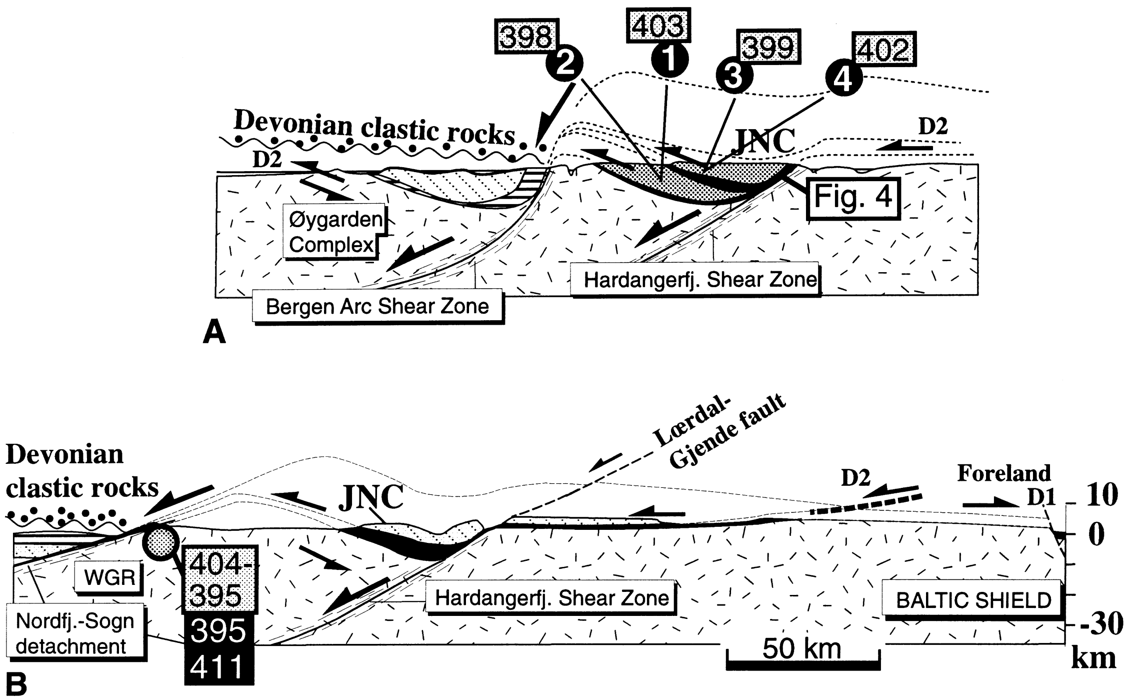

Fig. 2. Profiles across the Caledonides in southwestern Norway. Profiles indicated in Fig. 1. In profile A, the ages determined in this study and sampling positions (projected) are indicated, whereas in profile B the ages determined by Chauvet and Dallmeyer (1992) are shown.

1992; Wennberg and Milnes, 1994) and the NSDZ (e.g., Norton, 1987; Séranne and Séguret, 1987; Andersen and Osmundsen, 1994), and were possibly partly synchronous with but mostly later than the top-to-the-hinterland shearing along the décollement zone (Fossen, 1992).

There have been discussions regarding the timing of the extensional deformation in the southern Scandinavian Caledonides, and in particular whether the last thrusting event in the foreland (Oslo) region may have occurred simultaneously with extension in the hinterland/nappe region (Andersen, 1993; Fossen, 1993a). The youngest sediments affected by thrusting in the foreland (and elsewhere in the Scandinavian Caledonides) is the Ringerike Sandstone, which is of Wenlockian to lower Downtown (Pridoli or uppermost Silurian) age (Bockelie and Nystuen, 1985). Hence, the Caledonian thrusting history must have continued into the lowermost Devonian. There is considerable uncertainty regarding calibration of the Silurian–Devonian time scale (e.g., Gale et al., 1980), but the most resent compilation (Gradstein and Ogg, 1996) puts the Silurian–Devonian boundary at 417 Ma, which is taken as a maximum age of cessation of the Caledonian contractional history in the foreland. We will return to this discussion after presentation of the new $^{40}Ar/^{39}Ar$ data.

2.2. Previous $^{40}Ar/^{39}Ar$ work

Previous $^{40}Ar/^{39}Ar$ studies of micas in southwestern Norway are concentrated to the coastal areas adjacent to the NSDZ. Bryhni et al. (1971) reported a $^{40}Ar/^{39}Ar$ biotite plateau age of about 400 ± 2 Ma and a $^{40}Ar/^{39}Ar$ biotite isochron age of about 488 ± 2 Ma for a biotite in the WGR east of Hornelen (Fig. 1), whereas Lux (1985) presented a $^{40}Ar/^{39}Ar$ spectrum with a biotite plateau age of 375 ± 6 Ma from the WGR north of Hornelen. A more comprehensive study by Chauvet and Dallmeyer (1992) presented $^{40}Ar/^{39}Ar$ analyses of hornblendes and muscovite from the near-coastal region between the Hornelen basin and the Bergen Arcs (Fig. 1). They obtained plateau ages for eight muscovite concentrates that range from 393 to 403 Ma (displayed in Fig. 1), which they related to west-directed extensional shearing and unroofing of the footwall of the NSDZ. A single muscovite from the WGR east of the NSDZ gave a plateau age of 442 ± 1 Ma. In a preliminary report, Berry et al. (1995) described cooling ages of 446–449 Ma obtained from muscovite in the hanging wall to the NSDZ, which they related to early Caledonian orogenic activity, and younger (415–416 and 385–400 Ma) ages within the NSDZ.

Boundy et al. (1996) presented $^{40}Ar/^{39}Ar$ data for hornblendes and muscovites from the Bergen Arcs and the adjacent WGR close to the BASZ. They reported 450 Ma amphiboles and ca. 430 Ma muscovites from the Lindås Nappe (LN in Fig. 1) in the Bergen Arcs, whereas amphiboles in the WGR and in Precambrian rocks west of the Lindås Nappe yielded $^{40}Ar/^{39}Ar$ plateau ages that are much younger (395 ± 2, 409 ± 3 and 408 ± 3 Ma).

3. The Bergsdalen Nappes

The Bergsdalen Nappes comprise two major tectonic units, the Lower and Upper Bergsdalen Nappes, which are separated by an almost continuous zone of phyllonitic mica schist. The Bergsdalen Nappes are bounded to the southeast by the extensional HSZ, to the southwest by ophiolite and island-arc-related rocks of the Hardangerfjord Group (Færseth, 1982) and the Bergen Arc System (Kolderup and Kolderup, 1940; Færseth et al., 1977; Fossen, 1989), and to the north by the Western Gneiss Region. The Bergsdalen Nappes are structurally excised north- and eastward beneath the Jotun Nappe Complex.

The Upper and Lower Bergsdalen Nappes are composed of very similar lithologies, and appear to share a common pre-Caledonian history. A supracrustal sequence consisting of basic to intermediate metavolcanic rocks, metarhyolite, quartzite, conglomerate, quartz schist, and quartz-mica schist was intruded by gabbroic magma and, later, by a series of more granitic bodies and associated dikes. Several granitic bodies and metarhyolites record Rb–Sr whole-rock crystallization ages between 1274 and 953 Ma (Brueckner, 1972; Pringle et al., 1975; Gray, 1978). Hence, rocks in the Bergsdalen Nappes have been assigned a Precambrian age. However, at least some of the intercalated phyllites and mica schists may be Cambrian–Ordovician (e.g., Kvale, 1960).

Structural studies of the Bergsdalen Nappes (Fossen, 1993b) have documented evidence for very heterogeneous Caledonian deformation, with rocks ranging from practically unstrained to mylonitic. Compressional Caledonian deformation is locally preserved within more competent parts of the nappes, whereas in many places it has been reworked by subsequent hinterland (WNW)-directed shearing (extensional deformation). Both the Upper and Lower Bergsdalen Nappes are tectonically enveloped by phyllonitic mica schists where Caledonian contractional deformation has been obscured or completely obliterated by extensional back-sliding of overlying nappes.

4. Metamorphic conditions

Knowledge of the metamorphic evolution of the Bergsdalen Nappes and surrounding allochthonous units is limited because of the restricted occurrence of metamorphic index minerals. However, some constraints are provided by textures and parageneses. Growth of amphibole and biotite characterized mafic lithologies that were involved in thrusting. White mica, biotite, albite, orthoclase and occasionally garnet occur in quartzo-feldspathic rocks, and kyanite has been reported from the northwestern part of the Lower Bergsdalen Nappe (Gray, 1978). These characteristics indicate uppermost greenschist- to lower amphibolite-facies conditions in connection with peak metamorphism during thrusting (ca. 500ºC, >5 kbar; e.g., Winkler, 1979). $^{40}Ar/^{39}Ar$ analysis of an amphibole concentrate from the Lower Bergsdalen Nappe yielded a disturbed Proterozoic age spectrum (Fossen and Dunlap, 1998), implying that temperatures did not exceed ca. 500ºC for an extended period of time during the Paleozoic. Microtextures in rocks that were penetratively deformed during thrusting, but preserved from the subsequent extensional deformation, are characterized by extensive dynamic and static recrystallization. Samples 1–4 contain polygonal to interlobate quartz fabrics and equidimensional grains without evidence of much internal deformation. Polygonal fabrics are common in quartz domains in the mylonites. Remnants of dynamic recrystallization locally occur as very weak, lattice-preferred orientations (fig. 7 in Fossen, 1993b), and relics of internally strained older grains within a polygonal fabric in quartz-rich domains (fig. 6b in Fossen, 1993b). These features indicate that static (post-deformational) recrystallization occurred after thrusting.

Temperature conditions at the onset of the extensional, top-to-the-WNW shearing and the last part of the thrusting history appear to have been fairly similar. Although growth of amphibole or garnet during extension has not been identified, quartz fabrics are, in part, defined by equant, low-strain grains undistinguishable from blastomylonitic fabrics from preserved thrust zones (Fig. 3). In fact, mylonites that formed during thrusting and the subsequent WNW-directed shearing (extension) can only be distinguished by differences in asymmetry of kinematic indicators (Fig. 3a). This similarity indicates that, in addition to dynamic recrystallization, static recrystallization (annealing) occurred after top-to-the-WNW shearing.

Substantial, post-deformational recrystallization indicates that relatively high temperatures were maintained for some time after the top-to-the-WNW shearing event. In contrast, microfabrics along the HSZ do not display granoblastic textures, but instead record clear evidence for dynamic recrystallization of quartz to small grains oblique to the main foliation (Fig. 4). Furthermore, shear zones in nappes above the HSZ are predominantly brittle in nature (e.g., the Lærdal–Gjende fault; Milnes et al., 1997). A close geometric association between these brittle structures and the deeper, ductile basement shear zone (HSZ) indicates that they likely formed simultaneously at temperatures and crustal depth close to the brittle–ductile transition (ca. 10–15 km and 300–350ºC).

Depending on the availability of free water along grain boundaries, it has been proposed that temperatures in excess of ca. 400ºC are needed for static recrystallization to be efficient (e.g., Passchier and Trouw, 1996). Hence, temperatures maintained immediately after the top-to-the-WNW shearing were probably higher than $^{40}Ar/^{39}Ar$ closure temperatures of muscovite (see below), but probably dropped below the closure temperatures during subsequent movement along the ductile HSZ.

5. Sample description

Four muscovite concentrates have been prepared from representative samples collected within the Lower Bergsdalen Nappe and from the pelitic zone between the Lower and Upper Bergsdalen Nappes. Two concentrates (samples 1 and 2) are from Proterozoic quartzite conglomerates that were intruded by Mid-Proterozoic (Sveconorwegian) granites, and penetratively deformed during Caledonian thrusting. Very strong constrictional strains in these conglomerates are interpreted to have resulted during Caledonian thrusting (Kvale, 1948; Fossen, 1993b,c). These samples were collected in areas protected from post-contractional top-to-the-WNW shearing.

The other two muscovite concentrates (samples 3 and 4) were prepared from phyllonitic mica schists collected from the pelitic zone which marks a distinct tectonic break between the Upper and Lower Bergsdalen Nappes. This zone varies in thickness from <1 to several hundred meters, and is characterized by fabrics indicating very strong top-to-the-WNW shearing. The penetrative extensional reworking of this zone likely occurred because of its low competence and lateral continuity between the more massive and competent Bergsdalen thrust sheets. One sample was collected in Kvamskogen (sample 3), and the other in Fusa (sample 4). Both samples display mylonitic fabrics with associated S–C structures (e.g., Lister and Snoke, 1984) that unambiguously record a top-to-the-WNW sense of shear (Fig. 3a). These fabrics have been assigned to the post-collisional extensional deformation discussed above (D2 in Fossen, 1992, 1993b,c).

6. Analytical methods

The muscovite concentrates were analyzed using incremental-release $^{40}Ar/^{39}Ar$ analysis. The techniques used generally followed those described by Dallmeyer and Gil Ibarguchi (1990). Variations in flux of neutrons along the length of the irradiation assembly were monitored with several mineral standards, including MMhb-1 (Sampson and Alexander, 1987). Intralaboratory uncertainties have been calculated by statistical propagation of uncertainties associated with measurements of each isotopic ratio (at two standard deviations of the mean) through

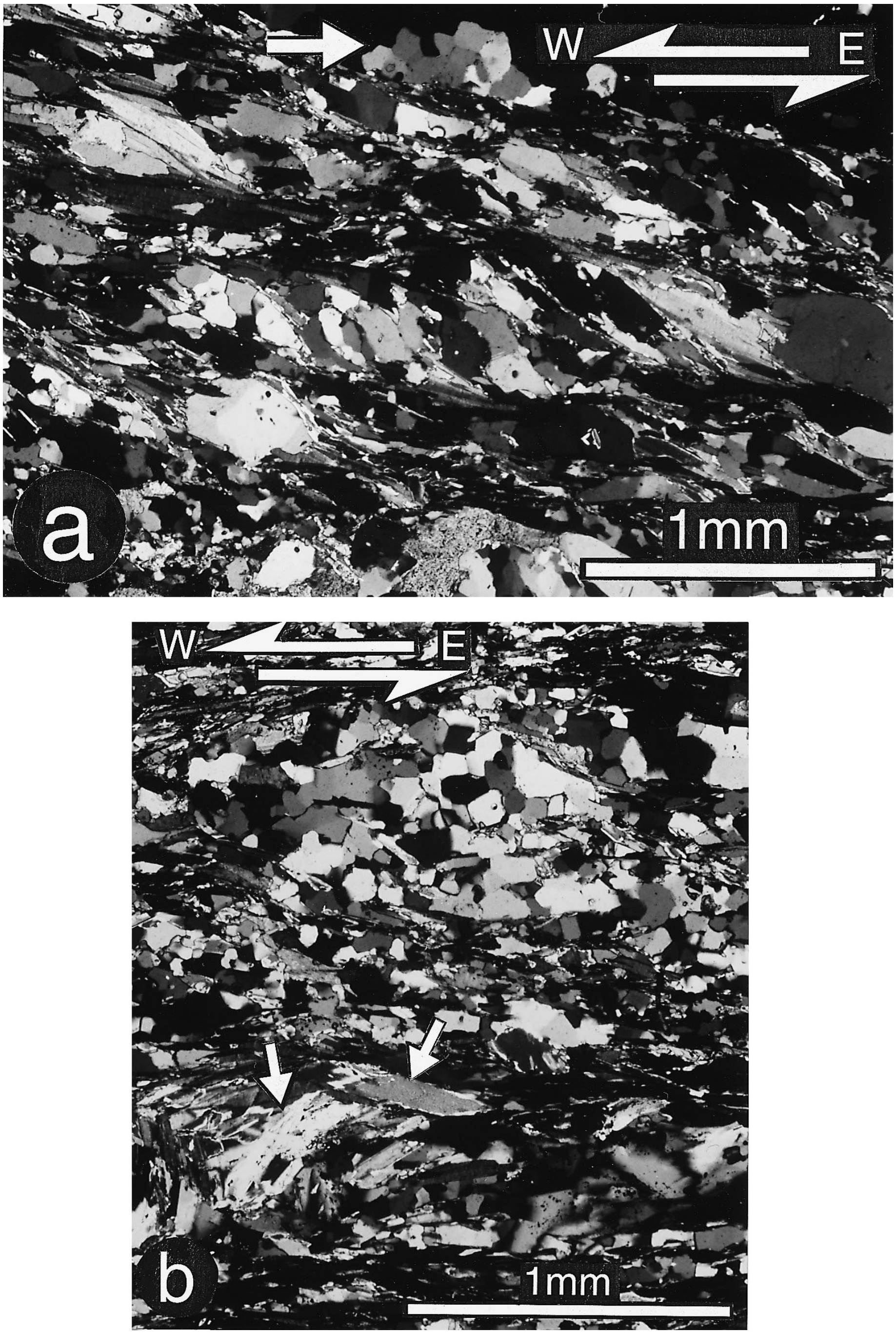

Fig. 3. (a) Asymmetric (S–C) fabric in phyllonitic mica schist in sample 3. Quartz grains are completely recrystallized, relatively strain-free, and form polygonal textures characteristic of static recrystallization (arrow). (b) Equidimensional polygonal quartz fabric also dominates quartz domains in sample 4 (central to upper part of picture, which shows an isoclinally folded and completely recrystallized quartz band). New growth of mica is also present (arrows).

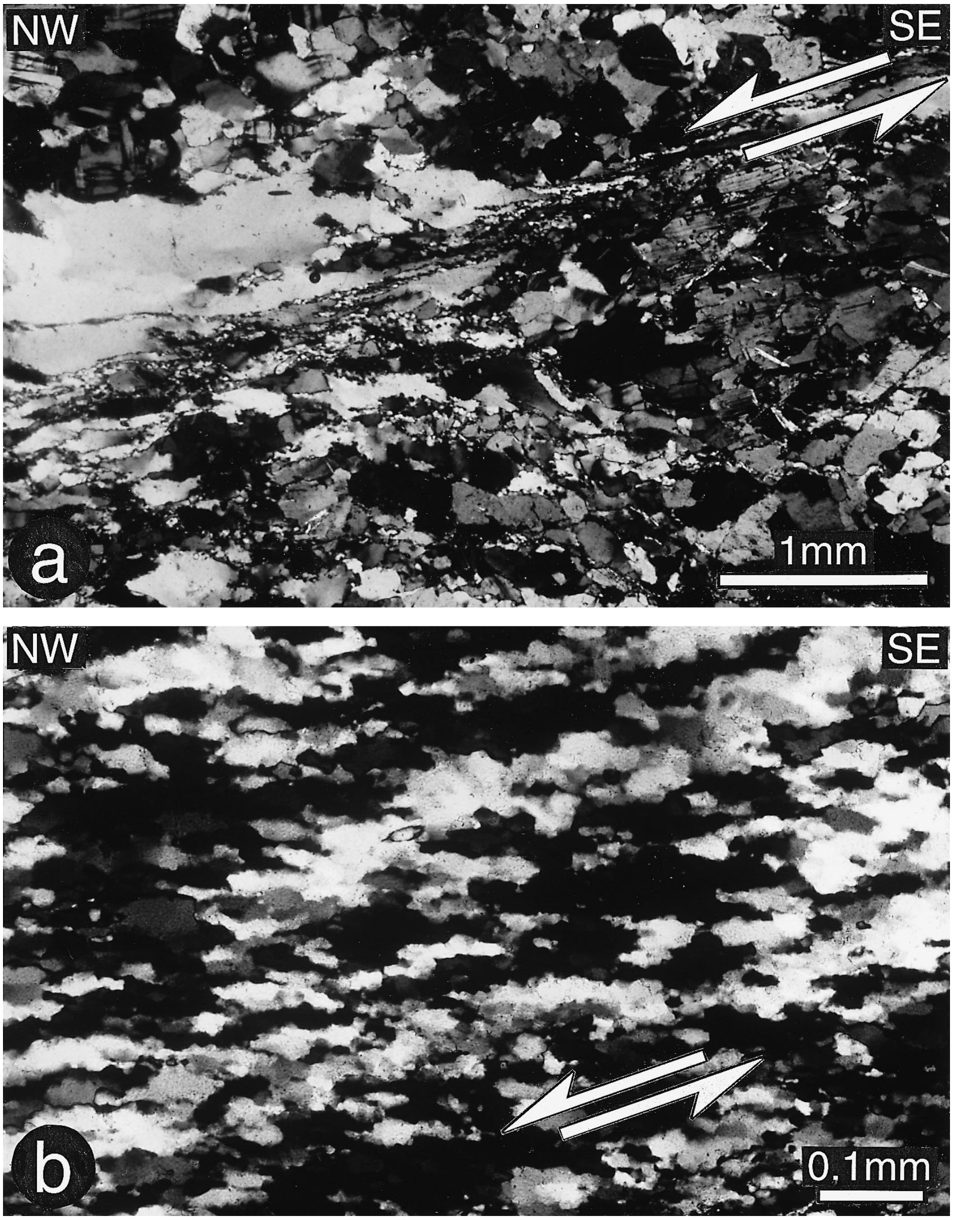

Fig. 4. (a) Microphotograph of microscale extensional shear band in Caledonian mylonites in rocks of the Bergsdalen Nappe along the Hardangerfjord Shear Zone. The grain size and shape-preferred orientation of quartz grains are different from those shown in Fig. 3, and indicate dynamic recrystallization at relatively low temperatures. (b) Close-up of quartz fabric from one of the extensional shear bands. Note the difference in scale and the angle between shape fabric (gently right-dipping) and foliation (left-dipping).

the age equation. Interlaboratory uncertainties are ca. $\pm$1.25–1.5% of the quoted age.

A 'plateau' is considered defined if the ages recorded by four or more contiguous gas fractions (with similar apparent K/Ca ratios) each representing >4% of the total ^{39}Ar evolved (and together constituting >50% of the total ^{39}Ar evolved) are mutually similar within $\pm$1% intralaboratory uncertainty. Analyses of the MMhb-1 monitor indicate that apparent K/Ca ratios may be calculated through the relationship 0.518 (±0.005) × $^{39}Ar/^{37}Ar$. Regression techniques followed the methods described by York (1969). A mean square of the weighted deviates (MSWD) has been used to evaluate isotopic correlations.

7. Results

The $^{40}Ar/^{39}Ar$ analytical data for the four muscovite concentrates are listed in Table 1, and are portrayed as apparent age spectra in Fig. 5. Coordinates of sample locations and petrographic description of the analyzed samples are provided in Appendix A.

The two muscovite concentrates from the Lower Bergsdalen Nappe and those from the pelitic zone between the Upper and Lower Bergsdalen Nappes display nearly concordant apparent age spectra, and record similar plateau ages which range between 403 ± 0.9 Ma (sample 1) and 398 ± 0.8 Ma (sample 2). Apparent K/Ca ratios are very large, with considerable uncertainties. Consequently, they are not shown with the age spectra. The K/Ca ratios display minor and non-systematic intrasample variations, suggesting that experimental evolution of gas occurred from compositionally uniform populations of intracrystalline sites. The plateau ages are considered geologically significant, and are interpreted to date the last cooling through temperatures required for intracrystalline retention of argon (see below).

8. Interpretation and discussion

The ca. 400 Ma $^{40}Ar/^{39}Ar$ plateau ages recorded by muscovite in samples with only Caledonian fabrics (samples 1 and 2) are identical to those from samples with younger top-to-the-WNW (extensional) fabrics. All of our $^{40}Ar/^{39}Ar$ ages are therefore considered to date cooling which followed the extensional top-to-the-WNW nappe translation.

An alternative interpretation would be that the ages are related to rejuvenation during the extensional top-to-the-WNW ductile deformation. Argon can be lost or redistributed during superimposed tectonometamorphic events as a result of complete

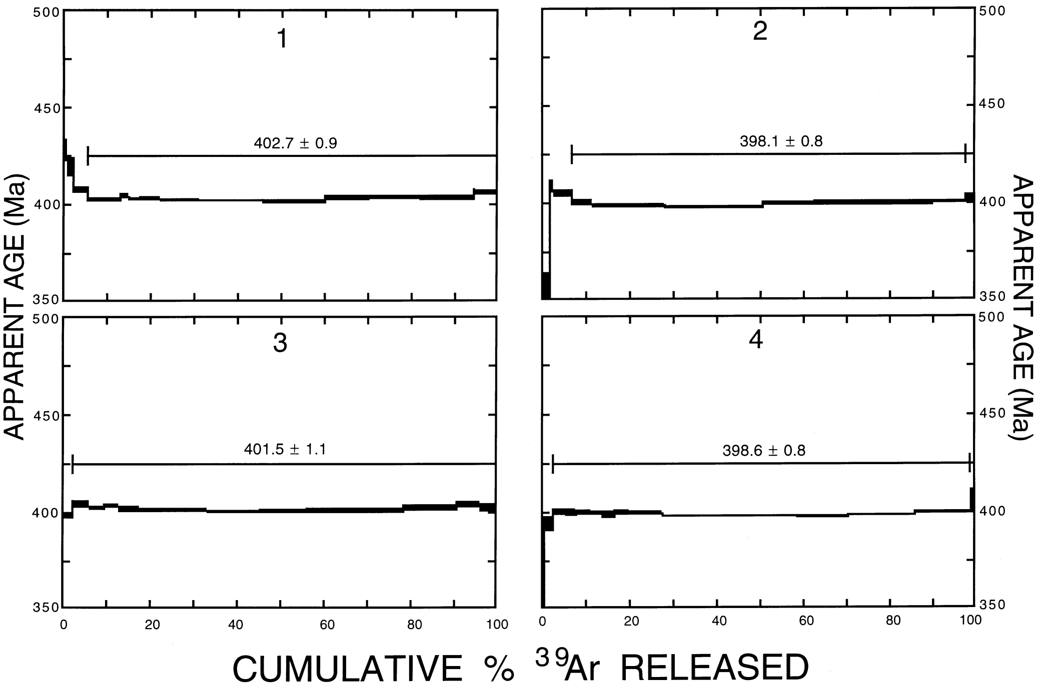

Fig. 5. $^{40}Ar/^{39}Ar$ apparent ages of muscovite concentrates from the Bergsdalen Nappes, SW Norway Caledonides. For locations, see Fig. 1. Analytical uncertainties (2σ intralaboratory) are represented by vertical width of bars. Experimental temperatures increase from left to right. Plateau ages are listed on each spectrum.

Table 1
$^{40}Ar/^{39}Ar$ analytical data for incremental-heating experiments on muscovite concentrates from the Bergsdalen Nappes, West Norway, Scandinavian Caledonides

Release temp. (ºC)	$(^{40}Ar/^{39}Ar)$ [a]	$(^{36}Ar/^{39}Ar)$ [a]	$(^{37}Ar/^{39}Ar)$ [b]	^{39}Ar % of total	$\%^{40}Ar$ non-atmos. [c]	$^{36}Ar_{Ca}$ %	Apparent age [d] (Ma)
Sample 1: J = 0.009308							
520	32.15	0.01151	0.002	1.06	89.41	0.00	427.7 ± 5.8
550	28.10	0.00010	0.009	1.22	99.88	2.55	418.7 ± 5.1
585	27.57	0.00125	0.011	3.13	98.64	0.24	407.1 ± 1.6
620	27.24	0.00129	0.004	7.56	98.59	0.08	402.4 ± 1.1
655	27.22	0.00081	0.008	2.09	99.10	0.26	404.1 ± 1.3
690	27.10	0.00079	0.006	2.44	99.12	0.21	402.5 ± 1.0
725	27.15	0.00089	0.006	4.75	99.01	0.18	402.8 ± 1.5
760	27.18	0.00119	0.004	8.92	98.68	0.09	402.1 ± 0.8
795	27.00	0.00062	0.005	4.63	99.30	0.22	401.9 ± 0.6
835	26.99	0.00079	0.004	14.18	99.12	0.12	401.0 ± 1.1
870	27.19	0.00101	0.008	10.07	98.88	0.21	403.0 ± 1.6
915	27.19	0.00092	0.003	11.87	98.98	0.09	403.3 ± 1.4
955	27.19	0.00095	0.004	12.27	98.94	0.11	403.1 ± 1.5
Fusion	27.33	0.00072	0.008	5.78	99.20	0.30	405.9 ± 1.9
Total	27.22	0.00102	0.005	100.00	98.89	0.18	403.3 ± 1.0
Total without 520–585ºC, fusion				94.58			402.7 ± 0.9
Sample 2: J = 0.008505							
520	28.05	0.00809	0.090	1.72	91.49	0.30	356.2 ± 8.6
560	31.20	0.00452	0.047	1.04	95.71	0.29	408.4 ± 3.8
610	30.02	0.00146	0.014	3.92	98.55	0.27	404.8 ± 2.2
660	29.64	0.00152	0.004	4.86	98.46	0.06	400.0 ± 1.8
710	29.31	0.00083	0.002	16.35	99.15	0.06	398.4 ± 0.9
760	29.15	0.00054	0.005	22.55	99.44	0.23	397.5 ± 1.1
810	29.33	0.00057	0.001	11.96	99.41	0.04	399.6 ± 1.0
860	29.33	0.00055	0.004	27.29	99.43	0.21	399.7 ± 1.2
910	29.32	0.00033	0.003	7.92	99.65	0.23	400.4 ± 0.9
Fusion	29.55	0.00066	0.009	2.41	99.32	0.39	402.0 ± 3.0
Total	29.33	0.00083	0.006	100.00	99.14	0.17	398.6 ± 1.3
Total without 520–610ºC, fusion				90.91			398.1 ± 0.8
Sample 3: J = 0.009022							
560	28.28	0.00298	0.028	2.34	96.87	0.25	398.3 ± 1.9
600	28.16	0.00109	0.009	3.99	98.84	0.22	404.1 ± 2.1
630	27.91	0.00074	0.003	3.20	99.20	0.12	402.1 ± 1.2
660	28.07	0.00099	0.003	3.42	98.93	0.08	403.3 ± 1.3
690	28.12	0.00160	0.007	4.72	98.30	0.11	401.6 ± 1.8
720	27.96	0.00118	0.007	6.83	98.74	0.15	401.2 ± 1.0
750	27.88	0.00096	0.007	8.72	98.97	0.20	401.0 ± 1.1
780	27.78	0.00076	0.005	11.95	99.17	0.19	400.3 ± 1.0
810	27.80	0.00079	0.004	10.81	99.14	0.13	400.6 ± 1.3
840	27.86	0.00095	0.004	10.50	98.97	0.11	400.8 ± 1.4
87	27.94	0.00117	0.004	11.84	98.74	0.10	400.9 ± 1.3
900	28.02	0.00109	0.005	12.20	98.83	0.13	402.2 ± 1.5
935	28.08	0.00089	0.003	5.48	99.04	0.09	403.8 ± 1.6
Fusion	27.96	0.00086	0.008	4.00	99.07	0.26	402.3 ± 2.1
Total	27.94	0.00104	0.006	100.00	98.88	0.12	401.4 ± 1.2
Total without 560ºC				97.66			401.5 ± 1.1

Table 1 (continued)

Release temp. (ºC)	(^{40}Ar/^{39}Ar) [a]	(^{36}Ar/^{39}Ar) [a]	(^{37}Ar/^{39}Ar) [b]	^{39}Ar % of total	%^{40}Ar non-atmos. [c]	^{36}Ar$_{Ca}$ %	Apparent age [d] (Ma)
Sample 4: J = 0.009531							
520	29.75	0.02318	0.009	0.55	76.95	0.01	356.0 ± 6.5
550	26.34	0.00247	0.022	1.84	97.22	0.24	394.0 ± 4.2
580	26.43	0.00127	0.008	3.04	98.56	0.18	400.0 ± 1.7
610	26.38	0.00122	0.014	2.36	98.62	0.32	399.5 ± 1.9
640	26.28	0.00089	0.005	3.54	98.98	0.16	399.5 ± 134
670	26.20	0.00068	0.008	2.52	99.22	0.33	399.3 ± 1.1
700	26.24	0.00097	0.006	2.53	98.89	0.15	398.7 ± 1.8
730	26.36	0.00110	0.006	3.54	98.74	0.16	399.7 ± 1.5
760	26.27	0.00086	0.005	7.55	99.01	0.17	399.4 ± 0.9
790	26.09	0.00064	0.004	10.72	99.25	0.17	397.9 ± 0.7
825	26.05	0.00052	0.004	11.48	99.39	0.21	397.8 ± 0.5
860	26.10	0.00069	0.005	8.79	99.20	0.19	397.8 ± 0.8
895	26.05	0.00060	0.006	11.72	99.30	0.25	397.5 ± 0.7
930	26.05	0.00037	0.007	15.66	99.56	0.51	398.4 ± 0.7
975	26.14	0.00034	0.004	12.92	99.59	0.31	399.9 ± 0.8
Fusion	26.55	0.00032	0.021	1.24	99.62	1.75	405.5 ± 6.3
Total	26.16	0.00078	0.006	100.00	99.12	0.28	398.4 ± 1.0
Total without 520–550ºC, fusion				96.37			398.6 ± 0.8

[a] Measured.
[b] Corrected for post-irradiation decay of ^{37}Ar (35.1 day half-life).
[c] [^{40}Ar$_{tot.}$–(^{36}Ar$_{atmos.}$) (295.5)]/^{40}Ar$_{tot.}$.
[d] Calculated using correction factors of Dalrymple et al. (1981); 2σ, intralaboratory errors.

or partial resetting (depending on the heating intensity and closure temperature of the mineral in question), reduction of grain size during shearing, or incorporation of 'extraneous' argon contained in intracrystalline fluids into the muscovites. This interpretation was favored by Chauvet and Dallmeyer (1992) for samples from the extensional NSDZ beneath the Devonian basins to the north of the Bergen Arcs, because a sample from the footwall outside of the extensional shear zone displayed a higher age than those from within the zone. In the present investigation, samples from both within and outside the extensional shear zones record identical ages; therefore complete rejuvenation of the muscovite argon system during extension is considered unlikely.

Evidence for substantial late- to post-deformational (static) recrystallization of both the contractional fabrics and the extension-related top-to-the-WNW fabrics suggests that temperatures of at least 400ºC were maintained throughout the top-to-the-WNW shearing. Most workers agree that the closure temperatures for muscovite are ca. 350ºC, although values as high as ca. 400ºC (Robbins, 1972; Wagner et al., 1977) and as low as ca. 325ºC (Snee et al., 1988) have been proposed. These values are consistent with interpretation of the ca. 400 Ma muscovite ages from the Bergsdalen Nappes to date cooling following top-to-the-WNW shearing, and in agreement with previously reported cooling ages from the WGR and NSDZ reported (Chauvet and Dallmeyer, 1992; Berry et al., 1995; Boundy et al., 1996).

Following top-to-the-WNW shearing (Mode I extension of Fossen, 1992; see Fig. 6b), extension was accomplished by movements along W- to NW-dipping extensional shear zones (Mode II extension; Fig. 6c). Large-scale rotation of the Bergsdalen Nappes is associated with these movements, as are semi-brittle faults in the Jotun Nappe Complex. Semi-brittle faults consistent with NW–SE extension also occur in the Precambrian crystalline rocks exposed west of the Bergsdalen Nappes (along the BASZ and in the Øygarden Complex), where they overprint local top-to-the-WNW fabrics. The faults are post-dated by Permian dikes, and are interpreted

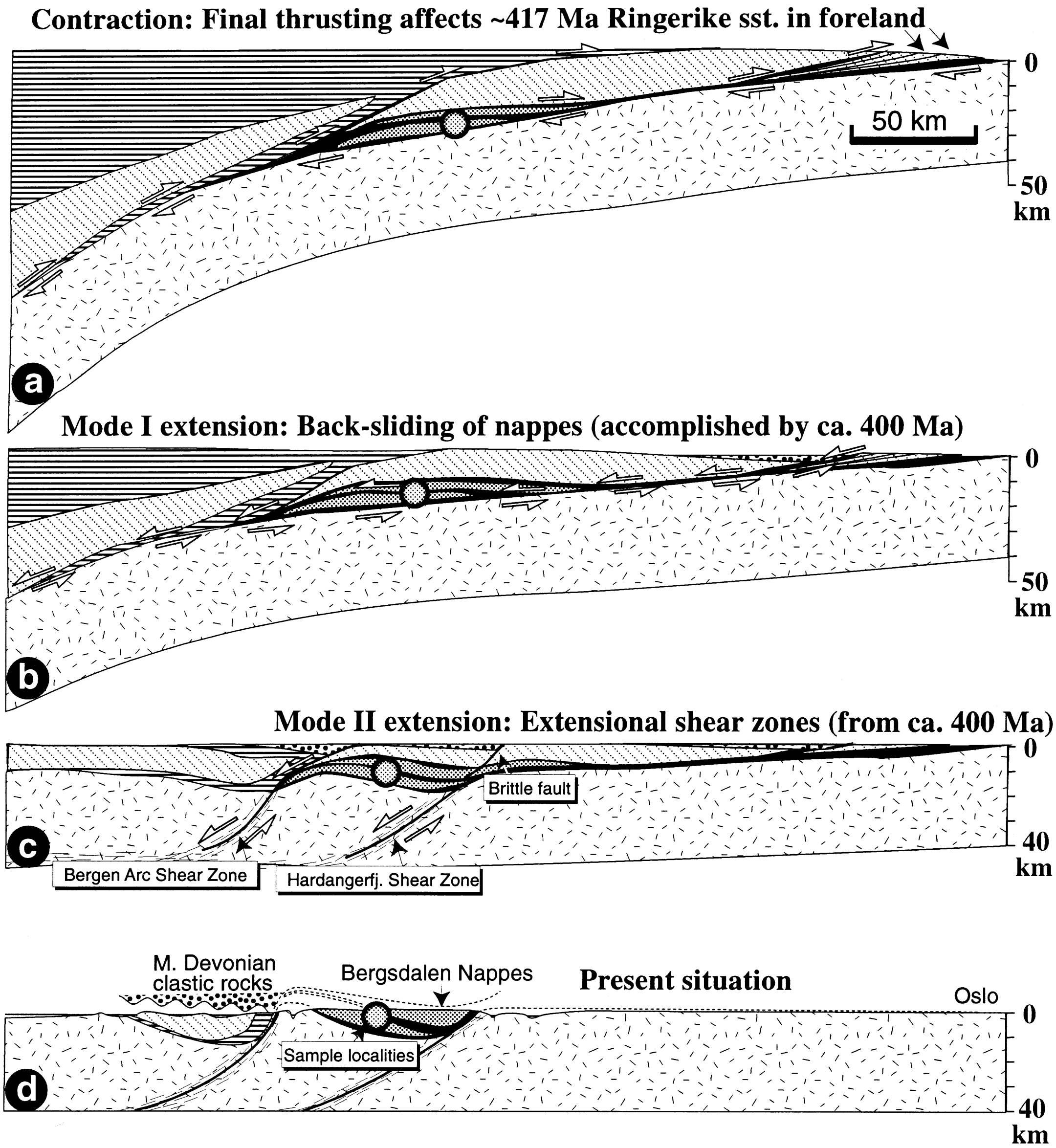

Fig. 6. Evolution of the Caledonides in southern Norway as shown by section A in Fig. 2 (extended to the east). (a) SE-directed thrusting during the Caledonian contractional history. The youngest sediments affected by this deformation is the uppermost Silurian (ca. 417 Ma; Gradstein and Ogg, 1996) Ringerike Sandstone in the foreland (Oslo). (b) Top-to-the-NW shearing along the basal décollement which separates basement from the orogenic wedge marks the onset of post-contractional extension. (c) Subsequent development of W- to NW-dipping extensional shear zones. $^{40}Ar/^{39}Ar$ ages of ca. 400 Ma presented in this report are interpreted as cooling ages associated with stages (b) to (c). (d) Present situation. See Fig. 1 for legend.

as an expression of Devonian exhumation and uplift following the top-to-the-WNW shearing event (Fossen, 1997).

The close association of brittle and ductile, low-temperature microfabrics from the HSZ indicates that temperatures passed the closure temperature for muscovite during Mode II extension. Thus, the cooling ages presented in this report probably date the Mode II extension in this section of the Caledonides. This interpretation implies that the several tens of kilometers of WNW-directed transport of the orogenic wedge (Mode I extension) was accomplished by about 400 Ma (Fig. 6a), and that subsequent extension proceeded by partly brittle movements along steeper shear zones and faults (Fig. 6c). Slightly younger (390–395 Ma) $^{40}Ar/^{39}Ar$ muscovite cooling ages from the northwestern margin of the Western Gneiss Region (Dallmeyer et al., 1992) indicate that this westernmost portion of the basement cooled through ca. 350ºC soon after the Bergsdalen Nappes, and that tectonic unroofing efficiently affected much of the Caledonian orogen in SW Norway at ca. 400 Ma.

Fossiliferous metasedimentary rocks of Wenlockian age are significantly involved in the Scandian thrusting history in the west Norway Caledonides (Thon, 1985), which involved large-scale thrusting and obduction of outboard terranes (Fig. 1) onto Baltica after ca. 425 Ma (e.g., Andersen et al., 1990). Likewise, Silurian Sm/Nd and U/Pb ages of eclogites in the Western Gneiss Region (WGR) indicate significant collisional tectonics at this time (Griffin and Brueckner, 1980). Considering the significant nappe translation and polyphase deformations involved in the post-425 Ma Scandian orogeny, it is generally believed that the contractional deformation outlasted the Silurian and probably even extended into the Devonian (e.g., Bryhni and Sturt, 1985). Evidence for this is found in the foreland region, where the uppermost Silurian Ringerike Sandstone was involved in contractional deformation. Accepting the time scale by Gradstein and Ogg (1996), the age of the Ringerike Sandstone is not younger than 417 Ma. There are thus ca. 17 m.y. between the youngest evidence of thrusting and the ca. 400 Ma $^{40}Ar/^{39}Ar$ cooling ages which date extension-related uplift. This time span is sufficient for the Caledonian contractional history (Fig. 6a) to be completed before the initiation of extension by NW-translation of Caledonian orogenic wedge and W- to NW-dipping shear zones (Fig. 6b,c); a model which is rooted in a consistent pattern of overprinting of contractional structures by extensional structures (Fossen, 1992, 1993b). However, thrusting probably continued for some million years after deposition of the Ringerike Sandstone, and extension initiated prior to the ca. 400 Ma cooling ages obtained in this study. The change from contractional to extensional deformation must therefore have happened very quickly, probably within a few million years. Furthermore, if the interpretation that the change from contraction to extension reflects a change from convergent to divergent plate motions at the end of the Caledonian history (Fossen, 1992; Rey et al., 1997), this change took place shortly before ca. 400 Ma. Additional dating of deformation in the Scandinavian Caledonides is needed to further constrain this change and test the generality of these interpretations.

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Appendix A. Detailed sample description

Sample 1. UTM coordinates: 32V LN 340081, north of Holmavatnet. Locality marked as loc. 34 on plate II in Fossen (1993a). Conglomerate consisting of quartz and quartzite pebbles with predominantly quartz, feldspar and mica in the matrix. Strongly deformed, showing constrictional strain (see figs. 8 and 16 in Fossen, 1993a). *c*-axis fabric diagram of this sample is shown in fig. 13 (loc. 34) in Fossen (1993a). The asymmetric girdle of this diagram indicates top-to-the-E sense of shear, interpreted as thrusting-related deformation (D1). In general, the rock exhibits a blastomylonitic fabric, with equigranular–interlobate to polygonal texture within the strongly stretched pebbles. Some larger quartz grains with interlobate shapes and subgrains/deformation bands are surrounded by somewhat smaller and less strained grains with more polygonal texture.

Sample 2. UTM coordinates: 32V LN 377080. Locality marked as loc. 313 on plate II in Fossen (1993a). This sample of strongly deformed conglomerate is similar to sample 1 with respect to mineralogy, fabric, kinematic indicators and strain (see fig. 16 in Fossen, 1993a for strain measurements). Equidimensional polygonal quartz fabric (except where recrystallization was hindered by micas) is interpreted to be the result of static recrystallization. Micas define the foliation while quartz shows no shape-preferred orientation due to static recrystallization in this blastomylonitic rock.

Sample 3. UTM coordinates: 32V LM 205833, road cut along the main highway between Eikelandsosen and Skjelbreidvatnet. Calcite–biotite–muscovite schist. Strong foliation defined by platy minerals and elongate quartz that curve into and out of shear bands, indicating top-to-the-WNW sense of shear (D2). Indications of recrystallization of quartz by grain-boundary migration and possibly subgrain rotation. Plagioclase compositions estimated optically to An_{10-20}. Equigranular–interlobate grain shapes in quartz-rich domains. Recrystallized or neocrystallized micas.

Sample 4. UTM coordinates: 32V LM 342978, road cut in sharp curve near Røyrli, Kvamskogen. Calcite–biotite–muscovite schist with shear bands consistent with top-to-the-WNW sense of shear. Calcite mainly located along shear bands. Quartz-rich lenses or domains show equigranular–polygonal fabric, indicating static recrystallization. A few relics of largely destroyed older grains occur. A photomicrograph of this sample is shown as fig. 26b in a previous report (Fossen, 1993a).

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