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The early Caledonian (Finnmarkian) event reassessed in Finnmark: $^{40}Ar/^{39}Ar$ cleavage age data from NW Varangerhalvøya, N. Norway

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Abstract

The relative significance of early (Finnmarkian) and late (Scandian) Caledonian deformation in N. Norway is uncertain. Early studies suggested pervasive Finnmarkian deformation whilst later results indicated a restricted Finnmarkian domain. The present work suggests it was more widespread than accepted and that inter Finnmarkian–Scandian deformation occurred. $^{40}Ar/^{39}Ar$ dating of 2–6 and 6–11 μm pelitic fractions from the lower to mid-greenschist facies Tanahorn Nappe (five samples; base Middle Allochthon) and the epizone Løkvikfjellet and Barents Sea Groups (three samples; North Varanger Region) in the north Scandinavian Caledonides show slightly discordant spectra. Most spectra from the Tanahorn Nappe preserve possible evidence of an early Caledonian event in the high temperature steps, with recoil/excess Ar effects in the low temperature steps; no pre-Caledonian relict component has been recorded. The results indicate Finnmarkian deformation continued to ~ 460 Ma, with Scandian reactivation at ~ 425–415 Ma. From the North Varanger Region, a strongly crenulated sample yielded plateau ages (444–442 Ma); means of combined young steps from weakly to uncrenulated samples gave 470–450 Ma, suggesting penetrative strike-slip deformation occurred in the late Finnmarkian to inter-Finnmarkian–Scandian period. No Scandian ages were recorded in the North Varanger Region. Reassessment of published data from the Laksefjord Nappe and Gaissa Thrust Belt suggests they were affected by Finnmarkian deformation.

Keywords: $^{40}Ar/^{39}Ar$ dating; Cleavage; Metamorphic evolution; Scandinavian; Caledonides; Finnmarkian

1. Introduction

The age of deformation events is a critical constraint when modelling orogenic belts. Despite this, isotopic age data are scarce in the northernmost Scandinavian Caledonides, where Sturt et al. (1978) ascribed most compressional deformation to a Finnmarkian event (~ 520–480 Ma) although subsequent work suggested much occurred in the Scandian event (~ 430–380 Ma; Dallmeyer, 1988; Dallmeyer et al., 1988, 1989).

This article describes $^{40}Ar/^{39}Ar$ data from the 2–6 and 6–11 μm separates of rocks from the Tanahorn Nappe (Middle Allochthon) and the tectonically underlying North Varanger Region (Fig. 1). These underwent mid-greenschist (just) to epizone grade peak

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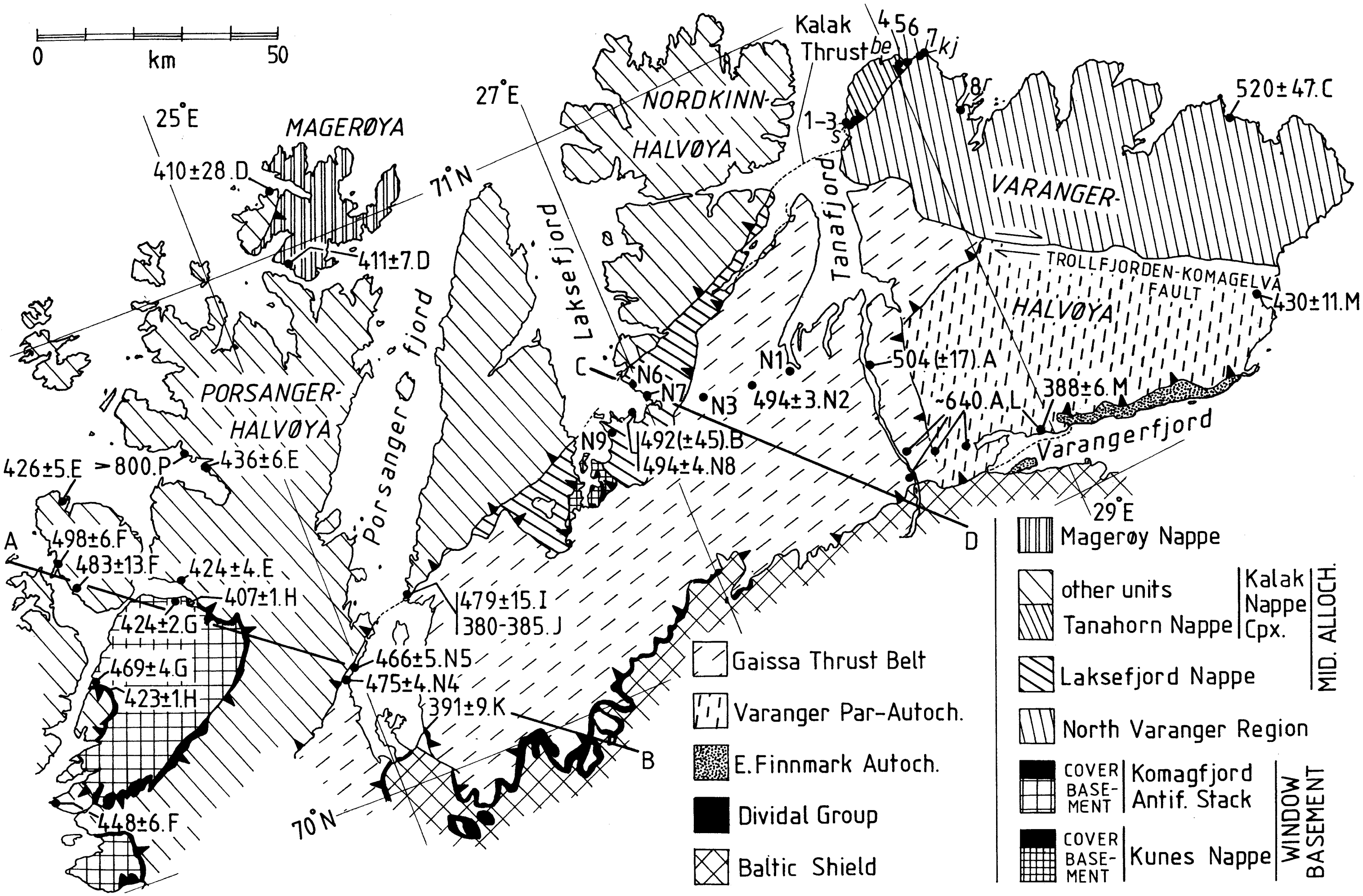

Fig. 1. Geological map of central and eastern Finnmark. 1–8 are localities of samples 1/D/97–8/D/97 of this study. Published isotopic data in Ma from (letter after age); A—Pringle; B—Sturt et al.; C—Taylor and Pickering; D—Andersen et al.; E—Dallmeyer muscovites; F—Dallmeyer amphiboles; G—Dallmeyer et al. (1988) basement; H—Dallmeyer et al. (1988) cover; I—Roberts and Sundvoll whole rock; J—Roberts and Sundvoll thin slab; K—Mitchell (in Roberts and Sundvoll). L—Dallmeyer and Reuter; M—Gorokhov et al.; N1–9—Dallmeyer et al. (1989). P—Daly et al. See text for details of methods used. Localities in NW Varangerhalvøya; s—Store Molvika; be—Berlevåg; kj—Kjølnes; r—Risfjord.

metamorphism, respectively; the ages recorded, therefore, are growth or resetting ages and not cooling ages. The data constrain evolutionary models of the region and suggest Finnmarkian deformation was more widespread and lasted longer than presently thought. The results also highlight difficulties in interpreting ^{40}Ar/^{39}Ar data from rocks metamorphosed to temperatures at or below the white-mica closure temperature, where relict material can be a problem.

Published data have been recalculated to modern decay constants (Steiger and Jäger, 1977; Dalrymple, 1979). In the absence of the analytical data, published errors have been given in brackets. Published MSWDs are given.

2. Regional background

The Scandinavian Caledonides in Finnmark (Fig. 1), which comprises several major allochthons correlatable with units extending throughout in the orogen, formed during SE- to ESE/E-directed compressional deformation. The highest unit is the Magerøya Nappe, a klippe of the Köli nappes (Upper Allochthon), in which shortening occurred at ca. 411 ± 7 Ma (MSWD 1.2; Andersen et al., 1982).

The underlying Kalak Nappe Complex forms the Middle Allochthon. In upper imbricates, between Sørøya and NW Porsangerhalvøya (Fig. 1), a common lithostratigraphy has been recognised (Ramsay et al., 1985). In lower imbricates, the stratigraphy gradually changes (Gayer et al., 1985) and correlation of rocks in the eastern part of the complex with those on Sørøya is not possible. In NW Varangerhalvøya, the Berlevåg Formation turbidites of the Tanahorn Nappe form the lowest imbricate in the complex (Levell and Roberts, 1977).

Peak metamorphism in the complex fell from upper amphibolite facies in the west to mid- to low-greenschist facies in the east (Tanahorn Nappe; Roberts, 1968; Teisseyre, 1972; Rice, 1985; Rice and Roberts, 1988; Rice et al., 1989b). Deformation was polyphasal (Roberts, 1968; Levell and Roberts, 1977; Gayer et al., 1985) and also polyorogenic; Daly et al. (1991) determined that some in parts of the complex, D1 and D2 occurred in a pre-800 Ma Porsanger Orogeny (Fig. 1), although the extent of this event is uncertain. Nepheline syenites gave U–Pb ages down to 520 ± 5 Ma, constraining the onset of Caledonian deformation (Pedersen et al., 1989) whilst ^{40}Ar/^{39}Ar dating of amphiboles from the central part of the complex gave Finnmarkian, Scandian and intermediate ages (Dallmeyer, 1988; Fig. 1). Muscovites, however, gave Scandian ages (~ 425 Ma; Dallmeyer, 1988), as did a Rb–Sr nepheline syenite pegmatite mineral isochron (406 ± 12 Ma; Sturt et al., 1978) and Rb–Sr whole-rock dating of migmatites on Magerøya (410 ± 28 Ma, MSWD 2.8; Andersen et al., 1982). Rb–Sr whole-rock dating of the basal mylonites in Porsangerfjord gave an age of 479 ± 15 Ma (MSWD 2.26), whilst Rb–Sr thin-slab dating gave late Scandian ages (380 ± 22 to 385 ± 26 Ma, MSWD 3.04 and 2.51, respectively; Roberts and Sundvoll, 1990).

The Laksefjord Nappe (Middle Allochthon; cf. Rice, 2001; Fig. 1) underwent early SE-directed and later ESE- to E-directed deformation. Sturt et al. (1978) obtained a Rb–Sr whole-rock age of 492 ± 45 Ma for the peak metamorphic epizone grade penetrative S1 cleavage (Rice et al., 1989a). Dallmeyer et al. (1989) made a K–Ar and ^{40}Ar/^{39}Ar study of this unit, but the results were thought to be inconclusive. These are reviewed in Discussion.

The western part of the Kalak Nappe Complex is underlain by the Komagfjord Antiformal Stack, comprising allochthonous basement unconformably overlain by Neoproterozoic to (?)early Palaeozoic sediments (Fig. 1; Window Basement; Gayer et al., 1987). Although basement rocks generally gave discordant ^{40}Ar/^{39}Ar whole-rock spectra, one pelite from near the roof thrust gave a Scandian plateau (424 Ma; Dallmeyer et al., 1988; Fig. 1). In the cover, which underwent epizone peak metamorphism (Rice et al., 1989a), Scandian ages have been recorded (425–400 Ma), but a plateau was developed in only one sample, from 1 m below the Kalak Thrust. All samples showed evidence of a high temperature, generally pre-520 Ma relict phase.

The Lower Allochthon comprises the Gaissa Thrust Belt, an external imbricate zone which underwent upper anchizone to diagenetic zone peak metamorphism (Rice et al., 1989a). Fifty percent shortening, predominantly ESE- to E-directed, occurred in the west, but the percentage shortening decreases south and east of Laksefjord (Chapman et al., 1985; Townsend et al., 1986). Dallmeyer et al. (1989) inferred that compressional deformation occurred after 440 ± 9 Ma; this is discussed below. Mitchell (in Roberts and Sundvoll, 1990) obtained a K–Ar whole-rock age of 391 ± 9 Ma from ultracataclasites forming the basal thrust in the Porsangerfjord area (Fig. 1), taken to constrain the last movements on the thrust plane. Eastwards, the Gaissa Thrust Belt merges into the Varanger Parautochthon and the East Finnmark Autochthon (Fig. 1). In the former, Pringle (1973) obtained a Rb–Sr whole-rock age of 504 ± 7 Ma from 'slates' (Fig. 1), interpreted as the age of cleavage formation. Further south and east, no Caledonian imprint has been found by either Rb–Sr whole-rock or ^{40}Ar/^{39}Ar 1–2 μm grain size dating (Pringle, 1973; Dallmeyer and Reuter, 1989). However, Gorokhov et al. (2001) obtained ages of 440–390 Ma from Rb–Sr analysis of the 0.1 μm fraction from Varangerfjord localities (Fig. 1).

In very simple terms, the outer part of the Baltoscandian continental margin was deformed in the Finnmarkian event (Kalak Nappe Complex). Subsequently, outboard oceanic units (Köli nappes) were emplaced over the Finnmarkian orogen, which was reactivated and thrust over the internal part of the continental margin, imbricating a basement topographic high (Window Basement) and then an external imbricate zone (Lower Allochthon).

2.1. Tanahorn Nappe and North Varanger Region

Northern Varangerhalvøya is separated from the southern part by the WNW–ESE trending Trollfjorden–Komagelva Fault, a dextral strike-slip structure with 200–300 km displacement (Bylund, 1994a). Fault movement occurred after emplacement of the Kalak Nappe Complex over the North Varanger Region, contemporaneous with shortening in the Gaissa Thrust Belt (Rice et al., 1989b).

Most of the area north of the Trollfjorden–Komagelva Fault comprises the Barents Sea Group and unconformably overlying Løkvikfjellet Group (up to 8.9 and 5.7 km thick, respectively; Johnson et al., 1978; Siedlecki and Levell, 1978), an area termed the North Varanger Region (Fig. 1). In the west, 6 km of the Barents Sea Group is absent, with only the basal Kongsfjord Formation turbidites remaining.

In western Varangerhalvøya, these rocks are folded into upright to steeply inclined NE–SW trending gently plunging folds, with a peak metamorphic epizone grade slaty cleavage, previously described as S1 (Roberts, 1972; Rice et al., 1989b). In eastern Varangerhalvøya, Taylor and Pickering (1981) obtained a Rb–Sr whole-rock age of 520 ± 47 Ma (MSWD 1.35), interpreted as the age of NE–SW oriented cleavage formation.

The overlying Tanahorn Nappe, which is the lowest part of the Kalak Nappe Complex, comprises 2.65 km of turbidites (Berlevåg Formation; Levell and Roberts, 1977). Rare biotite growth indicates metamorphism just reached mid-greenschist facies (cf. Teisseyre, 1972). Ductile deformation usually occurred in psammites, whereas only brittle deformation occurred in sandstones of the North Varanger Region. The nappe comprises southeast verging open to tight, asymmetric folds, on both large and small scales, with a dominant NNE-axial plunge and a penetrative axial-planar schistosity (S1 of Levell and Roberts, 1977).

The basal mylonites of the Kalak Nappe Complex exhibit a change from NW–SE oriented lineations in the upper part to WNW–ESE to W–E oriented in the lowest part (Townsend, 1987; Rice, 1998). Stretching lineations near Store Molvika show a similar pattern (compare samples 2 and 3/D/97 below) but those at the basal thrust east of Berlevåg show no variation in lineation direction, retaining a consistent WNW–ESE orientation (samples 4 and 5/D/97).

3. Sample material

Five samples were collected from the Berlevåg Formation, two from the Løkvikfjellet Group and one from the Barents Sea Group (Fig. 1). Grid coordinates given below are for the 1:50,000 NOR-2 map sheets Berlevåg (2336 I), Kongsfjord (2336 II) and Finnkongkeila (2336 IV). The analytical technique is given in Appendix A.

Although published accounts of the area propose a simple structural evolution, with an S1 cleavage being the penetrative fabric seen in the field (Roberts, 1972; Levell and Roberts, 1977; Rice and Reiz, 1994), a more complex picture was found in thin sections of the samples. Correlation of the Tanahorn Nappe deformations with those described elsewhere in the

Kalak Nappe Complex is not possible, as the intervening areas are too great for reliable interpolation. Note that deformation histories defined below are based on criteria observed within individual thin sections; with the exception of sample 5/D/97, this appears to give a consistent history.

3.1. Sample 1/D/97 (GR60955547 Map 2336 IV)—Berlevåg Formation

From the coast at Galbenjunni, north of Store Molvika (Fig. 1). Medium grey, friable phyllites. Penetrative S2 foliation strikes 218/18°WNW, with a stretching lineation in nearby grits plunging 12° towards 346°. Axis of a minor E-verging monoclinal D3 fold (*not* present in sample) plunges 26° to 351°. This folds S2, with an associated 1–3.5 mm spaced axial-planar cleavage (S3) striking 237/35°NW; other minor/micro-folds in the area have a chevron or crenulation geometry, depending on rock type. In thin section, the predominant minerals are quartz, chlorite and muscovite (+minor sphene, ore minerals, C-dust and rare tourmaline). The rock is penetratively deformed (S2), with alternating muscovite-rich and quartzofelspathic layers up to 0.08 mm wide, cut by weakly developed shear bands (C″) indicating top-to-SE movement. Evidence of an S1 fabric is poorly preserved in quartz-rich S2 microlithons. No F3 crenulation is present in the sample. No detrital mica has been seen in thin section.

3.2. Sample 2/D/97 (GR63155523 Map 2336 IV)—Berlevåg Formation

From north of the relict sea-stacks. Pale greenish, white weathering quartz-rich mylonites. Penetrative S2 foliation strikes 223/28°NW; strong stretching lineation plunges 28° to 313°. Shear bands (C″), indicating top-to-SE movement, are weakly developed in the sample. South of the sea-stacks, the mylonitic foliation is folded (F3) along axes plunging 17° to 327°, with an axial plane striking 180/53°E. In thin section, the main minerals are quartz and muscovite, with a semi-pelitic composition, forming an S2 foliation in somewhat anastomosing layers up to 0.13 mm thick, cut by shear bands (C″) with no new mineral growth. In the absence of C-dust pinning grain growth, the S2 fabric is coarser than in other samples. Relics of an S1 fabric are preserved in quartz-rich layers as obliquely oriented muscovites. In the nearby folded rock, a discrete S3 crenulation/pressure solution cleavage spaced at up to 1 mm is present, with some muscovite growth along crenulation surfaces. Some quartz grains (up to 0.9 mm size) are probably relict sedimentary clasts, augened by the foliation; no relict micas were observed. Chlorite is generally absent, except as a very minor late growth. Opaques and tourmaline are present and post tectonic carbonate is locally abundant, sometimes as up to 0.25 mm sized idioblastic grains.

3.3. Sample 3/D/97 (GR63705527 Map 2336 IV)—Berlevåg Formation

From the lowest outcrops on the hillside above the river terrace of Stuorrajåkka and below a small cliff. Medium to dark grey phyllites with psammitic mylonites above. In the phyllites, the foliation (S3) strikes 193/57°W, with an L3 stretching lineation plunging 55° to 283°. Occasional chevron folds are present, but not in the sample, with axes plunging 55° to 323°, with no noticeable associated cleavage. In quartzofelspathic rocks, S3 strikes 199/45°W, with a stretching lineation plunging 43° to 290°. Axes of tight to isoclinal folds have been rotated subparallel to this lineation and overturn to the NE. Shear bands (C″) all indicate a top-to-east-southeast movement. In thin section, quartz, chlorite and muscovite are present, with more muscovite than chlorite. Rare tourmaline, abundant C-dust and some 0.75 mm ore porphyroblasts are present. Evidence of four deformations has been found in thin section. The most prominent is a strong cleavage (S3) comprising alternating muscovite and quartzofelspathic layers from 0.01 to 0.05 mm thick. This is folded by a steep zonal crenulation cleavage (S4) with a wavelength of ~0.2 mm; no new mica grew in this event. The quartz-rich S3 microlithons include an oblique mica fabric (S2), which in turn locally truncates micas reflecting a still earlier fabric (S1). No sign of detrital mica was seen in thin section.

3.4. Sample 4/D/97 (GR78436208 Map 2336 I)—Berlevåg Formation

From the south side and east end of the short road cut east of Storsand. Dark grey, slaty rock, scarcely a phyllite, with a 1–3 mm platy texture. The dominant S3 foliation strikes 227/72°NW, with an intersection lineation plunging 22° to 040° and an L3 stretching lineation plunging 66° to 273°. In nearby sandstones, bedding strikes 210/75° NW and cleavage 206/84° NW, giving an intersection lineation plunging 23° to 023°. In thin section, the main minerals are quartz, muscovite and chlorite, with abundant C-dust, some chlorite porphyroblasts up to 0.12 mm size and 0.2 mm opaque porphyroblasts. Three fabrics have been recognised in thin section. A strong S3 pressure solution cleavage, spaced at 0.01–0.05 mm and associated with very tight to isoclinal micro-folds, is the slaty fabric seen in the field. Quartz-rich microlithons in this fabric carry oblique micas defining an S2 fabric. However, not all micas in the microlithons are parallel and many represent a still earlier cleavage (S1), reflecting the remains of crenulation microfolds. Rare small (0.05 mm) muscovites, of possible detrital origin, are present.

3.5. Sample 5/D/97 (GR79206221 Map 2336 I)—Berlevåg Formation

From the shore section, ca. 11 m from the roadside outcrop of the basal thrust, in Vargvika. Medium to pale grey, somewhat greenish semi-pelitic mylonite, with an obvious 1–3 mm platy texture. The dominant foliation (S2) strikes 221/67°NW, with a strongly developed L2 stretching lineation plunging 63° to 278°. The rocks are cut by quartz veins striking 256/13°N, with a quartz-fibre slickenside lineation plunging 06° to 282° and indicating top-to-east movement; curvature of the foliation, consistent with this movement, occurred adjacent to the quartz veins. Pelitic rocks are crenulated (not in analysed sample), with shear bands (C″) indicating top-to-southeast movement. In thin section, quartz, muscovite and chlorite are the main minerals, with C-dust, forming a slightly anastomosing essentially penetrative (S2) fabric. Sphene and an ore mineral are also present. Chlorite and quartz together form separate folia to muscovite, on a 0.5-mm scale, with oblique micas in the quartz-rich layers defining an earlier fabric (S1). Weak shear bands (C″) are present, but no new mineral growth occurred. Muscovite flakes up to 0.75 mm long and 0.15 mm thick are detrital. Abundant quartz and plagioclase grains (0.05 mm diameter) are probably also detrital and form spheroidal clasts, imparting a strong augen texture.

3.6. Sample 6/D/97 (GR80606252 Map 2336 I)—Løkvikfjellet Group, Stordalselv Formation

From a very low road-cut exposure north of the road, ca. 1 km west of the Kjølnes lighthouse road. Dark grey slate with essentially uncleaved sandstones. Cleavage (S2) strikes 040/87°SE and has a ca. 1 mm spacing. A fine crenulation (F3) plunges 03° to 220°, with minor kink-band axes plunging 69° to 219°. In thin section, the main minerals are quartz, muscovite and chlorite, with abundant C-dust; pelitic and quartzofelspathic layers alternate on a 0.5-mm scale. Abundant spherical quartz porphyroclasts (0.18 mm) and muscovites up to 0.06 mm long are of detrital origin. Chlorite forms porphyroblasts/aggregates up to 0.5 mm size, elongate parallel to the relict sedimentary layering. Three cleavages are present. Relics of an S1 cleavage are clearly preserved in S2 microlithons, making an angle of ca. 15–20° with the dominant cleavage (S2) seen in pelitic bands, which is parallel to the compositional layering. Some micas parallel to S2 are present in the quartz-rich bands. A later, very strong spaced pressure-solution cleavage (S3, spaced at 0.02–0.15 mm) is developed in the mica-rich layers, at an angle of −10° to −25° to S2, forming the fine crenulation (S3) seen in outcrop, but no evidence of new mineral growth has been seen in S3. Compared to S2, S1 dips steeply to the west, whilst S3 is at a lower angle.

3.7. Sample 7/D/97 (GR81766273 Map 2336 I)—Løkvikfjellet Group, Stordalselv Formation

From outcrops on the northwest side of the bay, west of the house immediately south of the lighthouse building at Kjølnes. Pale sandstones alternating on a large scale with dark grey to black slates. Bedding strikes 230/82°NW. In thin section, the main minerals are quartz, muscovite and chlorite, with some epidote and abundant C-dust, forming alternating quartz–muscovite and muscovite–chlorite folia, defining the main cleavage (S2), which is axial planar to microfolds. Chlorite porphyroblasts are up to 0.25 mm size. Pressure solution seams within the pelitic layers are spaced at 0.05 mm; in the intervening microlithons, an earlier fabric (S1) is seen as variably oriented micas, often with their (001) planes at a high angle to S2, reflecting relics of crenulation fold hinges. Some relatively large micas (0.15 mm long) are of detrital origin.

3.8. Sample 8/D/97 (GR83864870 Map 2336 II)—Barents Sea Group, Kongsfjord Formation

From outcrops between the road and shore in the SE corner of Risfjord. Dark grey slates with thin, pale to medium grey sandstones. Bedding strikes 041/79°SE, with an S2 cleavage striking 040/63°SE, indicating the inverted limb of a fold, with an intersection lineation plunging 03° to 041°. A nearby fold axis (F3) plunges 07° to 021°, with an axial plane striking 020/44°SE. In thin section, the main minerals are muscovite, quartz, C-dust, abundant opaque porphyroblasts up to 0.15 mm long and 0.05 mm wide and rare chlorite. Three fabrics have been distinguished in the sample, the youngest of which, S3, is a moderately developed crenulation fabric spaced at 0.01–0.07 mm, cutting obliquely across an earlier fabric (S2) at ca. 20–25°, with relatively little or no neocrystallization. S2 is essentially penetrative in pelitic rocks, although very rarely an oblique fabric (S1) of fine micas and (?)carbonaceous dust trails can be seen in S2 microlithons at an angle of ca. − 40°. Over the thin section, S1 relics have a relatively constant orientation, which is not parallel to bedding and cannot, therefore, be a diagenetic dewatering/compaction fabric. It is, however, subparallel to the long axes of opaque porphyroblasts, which are clearly wrapped around by the S2 fabric. Some detrital micas, up to 0.5 mm long, are present.

4. Results

The ^{40}Ar/^{39}Ar spectra are shown in Figs. 2 and 3; analytical results can be obtained from the first author. A detailed summary of the data is given in Table 1. ‘Plateaux’ consisting of < 50% evolved gas are referred to as a mean age for a group of combined steps.

For sample 1/D/97, the two size fractions gave the same total gas ages, at 446–445 Ma. The 2–6 μm fraction gave a relatively poor plateau (430.1 ± 7.9 Ma), based on four steps, with 61% of the total gas evolved. A single small high temperature step, with 1.9% gas, gave an age of 462 Ma, whilst the lower temperature steps also recorded older ages. The 6–11 μm fraction has 60% of the gas in the age range of 435–415 Ma, but this is not even a poor plateau; the youngest component was associated with 17% evolved gas. Two steps define a time at ca. 434 Ma, similar to the plateau in the finer fraction, but with only 29% gas. Lower temperature steps record older ages whilst the last, high temperature step, with 8.3% gas, has an age of 463 Ma, similar to the finer fraction. Essentially, the two grain size fractions gave very similar release patterns.

Both grain sizes gave the same total gas ages (462–468 Ma) and similar plateau ages in sample 2/D/97. The plateaux, at 459–463 Ma, are defined by 77% (five steps) and 69% (six steps) of the evolved gas, for the 2–6 and 6–11 μm fractions, respectively. In the coarser fraction, no evidence of older ages is observed in the lower temperature steps and this forms only a minor component of the finer fraction. Both fractions show slightly elevated higher temperature ages (472 Ma, 24% gas, and 483 Ma, 28% gas), although the highest temperature step in the 2–6 μm fraction has an anomalously young age (433 Ma, 6.4% evolved gas).

For sample 3/D/97, the total gas ages of 434–438 Ma are ca. 12 Ma older than the plateau ages (423–424 Ma), the latter being defined by 52–68% of the gas evolved, from three and four steps, respectively. There is no evidence of older, high temperature steps; instead, anomalously young ages are developed in both samples (361 and 399 Ma, both 2.3% evolved gas). Both grain sizes also show markedly older ages in the low temperature steps. Again, therefore, the two size fractions gave similar results.

In sample 4/D/97, both grain sizes show older ages in both low and high temperature steps, the latter reaching ages of 519 Ma in the coarser size fraction; this is the oldest age recorded in this study. In the 2–6 μm fraction, these effects are so large that no plateau can be defined; the central two steps give a mean age of 415 Ma with 29% gas, much younger than the total gas age (446 Ma). In the coarser fraction, the total gas age and plateau age are the same (469–465 Ma), but only because the youngest, lowest temperature step ‘balances’ the older high temperature steps. The

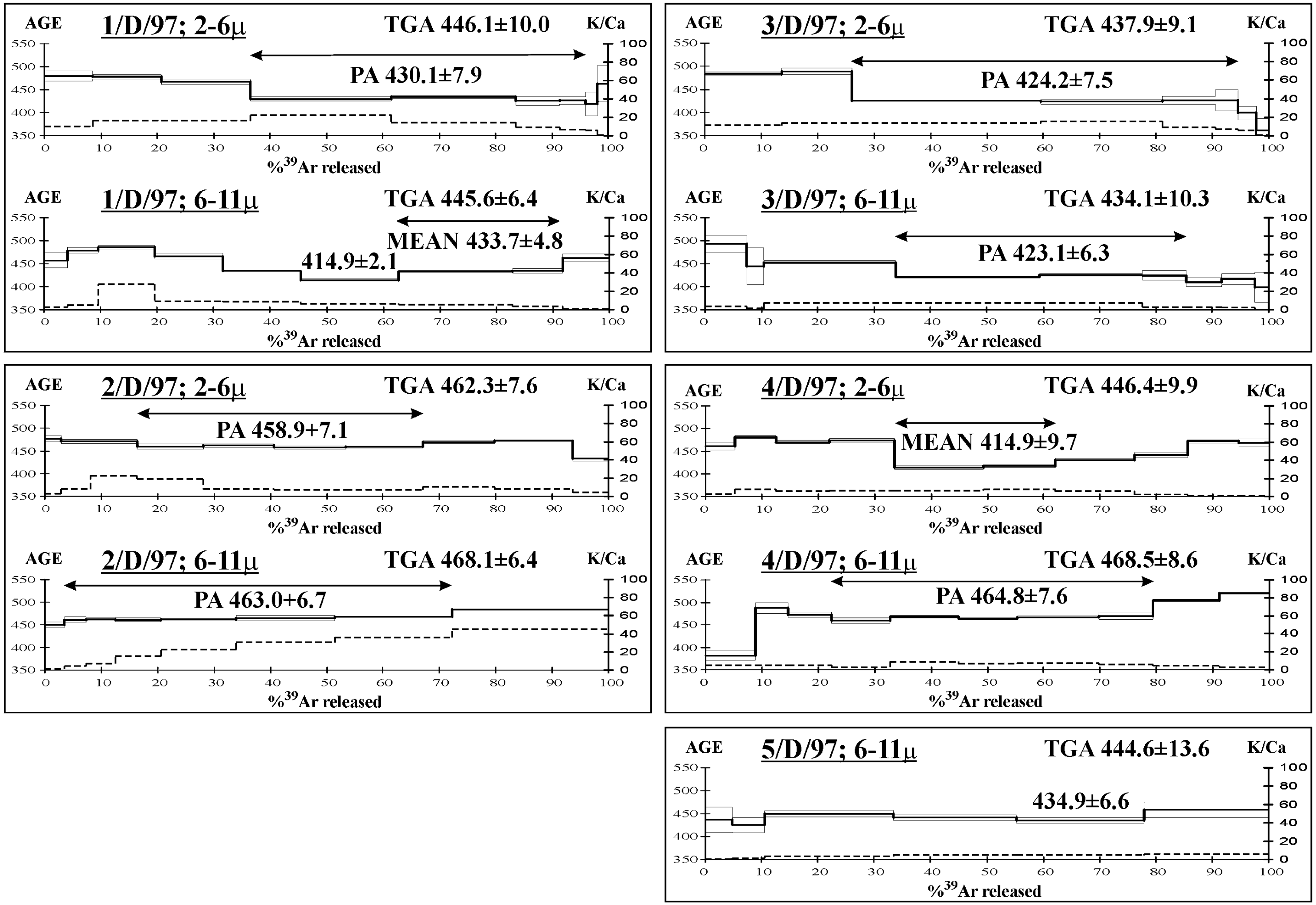

Fig. 2. Tanahorn Nappe—^{40}Ar/^{39}Ar release profiles. Drawn errors are 1σ, quoted errors include a further ± 0.4% on the J value; dashed line is the K/Ca ratio. Ages in Ma.

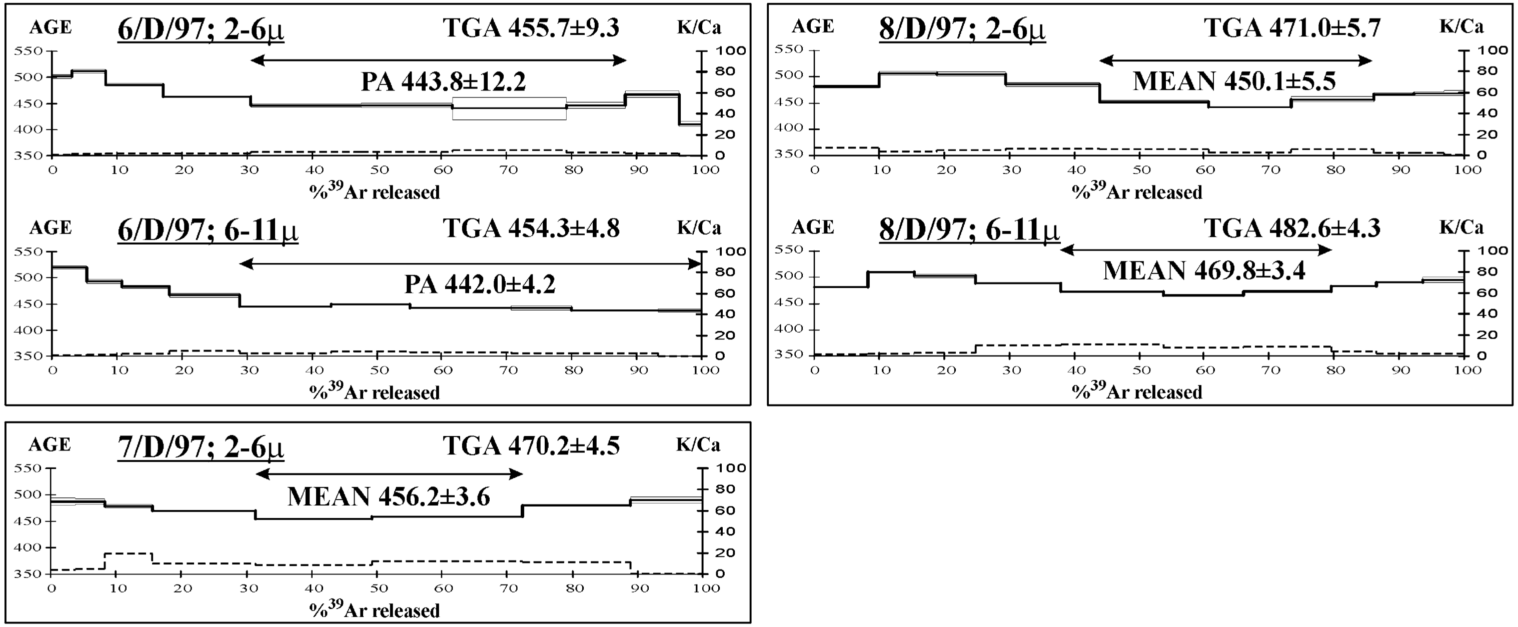

Fig. 3. North Varanger Region—^{40}Ar/^{39}Ar release profiles. Drawn errors are 1σ, quoted errors include a further ± 0.4% on the *J* value; dashed line is the K/Ca ratio. Ages in Ma.

Table 1
^{40}Ar/^{39}Ar data from the Tanahorn Nappe (TN) and North Varanger Region (NVR)

Sample	Formation	2–6 μm fraction						6–11 μm fraction					
		TGA	PA/*MA*	%Gas	Steps	Old	%Gas	TGA	PA/*MA*	%Gas	Steps	Old	%Gas
1/D/97	Berlevåg (TN)	446.1 ± 10.0	430.1 ± 7.9	61	4–7	462	1.9	445.4 ± 6.8	*433.7 ± 4.8*	*29*	7–8	463	8.3
2/D/97	Berlevåg (TN)	462.3 ± 7.6	458.9 ± 7.1	65	4–8	472	6.4	468.1 ± 6.4	463.0 ± 6.7	69	2–7	483	27.8
3/D/97	Berlevåg (TN)	437.9 ± 9.1	424.2 ± 7.5	68	3–6	–	–	434.1 ± 10.3	423.1 ± 6.3	52	4–6	–	–
4/D/97	Berlevåg (TN)	446.4 ± 9.9	*414.9 ± 9.7*	*29*	*5–6*	468	5.4	4698.5 ± 8.6	464.8 ± 7.6	57	4–8	519	8.9
5/D/97	Berlevåg (TN)		No data					444.6 ± 13.6	*(434.9 ± 6.6)*	(23)	–	458	22.1
6/D/97	Stordalselv (NVR)	455.7 ± 9.3	443.8 ± 12.2	58	5–8	467	8.3	454.3 ± 4.8	442.0 ± 4.2	71	5–10	–	–
7/D/97	Stordalselv (NVR)	470.2 ± 4.5	*456.2 ± 3.6*	*41*	*5–6*	490	11.0		No data				
8/D/97	Kongsfjord (NVR)	471.0 ± 5.7	*450.1 ± 5.5*	*42*	*5–7*	468	3.1	482.6 ± 4.3	*469.8 ± 3.4*	*42*	*5–7*	494	6.4

Errors quoted are 1σ plus a further ± 0.4% on the J value.
Results in italics refer to mean age of combined step (*MA*); those also in brackets refer to age of youngest step. Old: age of oldest high temperature step.

plateau age is defined by 57% evolved gas, using five steps.

For sample 5/D/97, only data from the 6–11 μm size fraction is available. This shows a more homogeneous release pattern compared to some of the other samples, although no plateau can be defined. The total gas age is 445 Ma, with the youngest increment in the saddle at 435 Ma (23% gas). The high temperature steps reach an age of 458 Ma, with 22% gas.

The data from sample 6/D/97 shows distinctly older ages in the low temperature steps, but little evidence of older, high temperature domains, and with identical total gas ages from the two fractions (456 and 454 Ma). The finer size-fraction has a plateau age of 444 Ma, (66% evolved gas), whilst the coarser gives the same plateau age, at 442 Ma, from 71% gas. In the finer fraction, the highest temperature step gave an anomalously young age (410 Ma, 3.5% evolved gas).

Only data from the 2–6 μm size-fraction is available for sample 7/D/97; this shows the combined effects of older ages in low and high temperature steps, the latter giving an age of 490 Ma, with 11% gas evolved. A mean of two steps and 41% evolved gas gave an age of 456 Ma, with a total gas age of 470 Ma.

Sample 8/D/97 suffers from older ages in both low and high temperature steps with total gas ages of 471 and 483 Ma for the fine and coarse size fractions, respectively. Mean ages of 450 and 470 Ma (both 42% evolved gas), using three steps from both fractions, were obtained. The youngest increment gave an age of 441 Ma (12.7% evolved gas) from the finer grain size fraction, whilst that from the coarser fraction gave 465 Ma (12.3% evolved gas).

5. Discussion

5.1. Interpretation of data

Excess Ar and/or recoil effects, both of which give older apparent ages in low temperature steps, are exacerbated by analysing finer grain sizes (cf. Dickin, 1997) and hence occur in most of the spectra presented here. As the samples were collected from units underlain by pelitic lithologies, which would have been warmer and thus still releasing ^{40}Ar after the system had essentially closed in the samples, the consequent upwards ^{40}Ar diffusion would have contaminated the samples. Thus excess Ar is thought to have been the main cause of the older, low temperature steps, although recoil may have contributed.

Both detrital components and multiple deformations (or multiple orogenic events) may cause older ages in higher temperature steps. Although higher metamorphic temperatures, higher strains (increased defect density), smaller grain sizes and increased fluid flow all increase the probability of relict grains being isotopically reset, the temperature interval at which grains of a particular size and phase are reset isotopically is poorly understood in detail. For muscovite, this interval has been estimated at *around* 350 °C (cf. McDougall and Harrison, 1999). Note that in Barrovian $P-T-t$ cycles, typical of collisional events, rocks may spend a very long time close to T_{max} (Thompson and England, 1984), considerably enhancing the resetting of relict material, especially finer grains, if T_{max} lies near, rather than clearly above the closure temperature interval.

Peak metamorphism in the Tanahorn Nappe lay around the lower (= epizone) to middle greenschist facies boundary; quartz usually shows evidence of ductile deformation whilst biotite is a rare phase (Teisseyre, 1972; Rice et al., 1989b). In the North Varanger Region, epizone conditions were never exceeded and no ductile deformation occurred in sandstones (Roberts, 1972; Rice et al., 1989b). This suggests peak temperatures of ca. 350–400 and ~ 300 °C for the two areas, respectively, i.e. broadly around the closure temperature interval of white micas. Thus the ages determined are essentially growth, or partial resetting ages and not cooling ages. Since fine grain sizes were analysed, resetting of detrital grains may well have been essentially complete. Subsequent, post-peak metamorphic crenulations would have disturbed the system with younger growth components, leaving relict early deformation ages in high temperature steps.

In combination, these processes give a saddle-shaped profile, with no, or only a relatively poor plateaux; the former only constrain the upper age limit of the last major crystallization. Anomalously young ages from high temperature steps may be due to low intensities (i.e. machine uncertainty) or loss of radiogenic Ar as different minerals begin to loose gas.

The Berlevåg Formation samples (1-5/D/97) generally show slightly saddled profiles with total gas ages between 434 and 469 Ma (Table 1) and plateau ages between 423 and 464 Ma. Mean combined step ages are younger, down to 414 Ma. Although most samples have older, high temperature steps, only in the 6–11 μm fraction of sample 4/D/97 is this a pre-Caledonian age, at 519 Ma; even this could be an early Caledonian age, comparable to that recorded in E. Varangerhalvøya (Taylor and Pickering, 1981; Fig. 1). Further, the plateau, or mean combined step ages for the two grain sizes analysed are generally the same (Fig. 4); only in sample 4/D/97 is this not the case. A detrital effect should be more prominent in the coarser fraction, but only slight differences in the spectra from the two sizes has been recorded in several cases.

The high temperature steps from the Berlevåg Formation samples are not particularly old and some overlap with the plateau ages from other samples. Excepting the 519 Ma age from sample 4/D/97, the high temperature ages clearly lie in the early to ‘middle’ Caledonian range (Table 1; Fig. 4). Thus, as detrital mica is uncommon in thin sections and it seems likely that small detrital grains were isotopically reset, the high temperature steps are interpreted as relics of early Caledonian events. Similarly, there is no evidence of a relic of the pre-Caledonian Porsanger Orogeny, which encompasses D1 and D2 in some western parts of the complex (Fig. 1; Daly et al., 1991).

The ages from sample 2/D/97 are amongst the oldest obtained. This is ascribed to the absence of S3 formation and the larger muscovite grain size. The results (459 ± 7 and 463 ± 7 Ma) overlap with the Rb–Sr whole-rock 479 ± 15 Ma (MSWD 2.26) age of the Kalak mylonites from Porsangerfjord (Roberts and Sundvoll, 1990; Fig. 1) and are also the same as the plateau age from the 6–11 μm fraction of sample 4/D/97, in which S3 developed, and are similar to many high temperature step ages. This suggests that initial deformation (D1 and D2) within the Tanahorn Nappe was a Finnmarkian event. Sample 1 also lacks D3 deformation, but this has a pelitic composition and abundant C-dust, pinning micas to a much smaller grain size.

In sample 3/D/97, a very strong, almost penetrative S3 fabric developed; consequently, the obtained plateau ages (423 and 424 Ma) reflect the age of S3; D3 in the Tanahorn Nappe was thus a Scandian event. This age is consistent with the mean age of two combined steps in sample 4/D/97 (415 Ma), in which

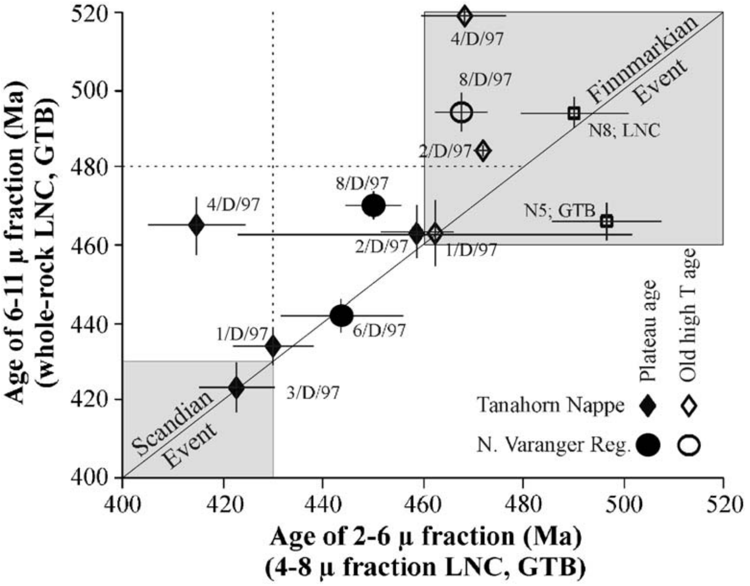

Fig. 4. Comparison of ages, with error bars, from fine and coarse grain sizes. Axis labels in brackets refer only to samples N5 and N8, from the Gaissa Thrust Belt and Laksefjord Nappe Complex, respectively (Dallmeyer et al., 1989).

S3 also occurs. The Scandian ages from sample 3/D/97 are associated with E- to ESE-directed stretching lineations, typical of late Caledonian movements at the base of the Kalak Nappe Complex (Townsend, 1987; Rice, 1998), whereas sample 2/D/97, with SE-directed lineations, gave an early Caledonian age.

Comparison of the structural history and ages (Table 2) shows that younger ages generally came from samples with more extensive post-S2 deformation, even though no (or little) new mineral growth occurred. However, the increased defect density due to crenulation and contemporary pressure solution, attesting to fluid flow, would have enhanced isotopic resetting. The exception is sample 5/D/97; the stretching lineation direction is typical of late Caledonian movement, suggesting the dominant fabric is S3,

Table 2
Comparison of structural history and $^{40}Ar/^{39}Ar$ age

Sample	S1	S2	Lineation	S3	S4	2–6 µm age	6–11 µm age
Tanahorn Nappe							
1/D/97	relic	pen + weak C″	L2 NNW–SSE	–	–	430 ± 8 P	434 ± 5 M
2/D/97	relic	pen + weak C″	L2 NW–SE	–	–	459 ± 7 P	463 ± 7 P
3/D/97	relic	microlithon	L3 WNW–ESE	strong cren	weak cren	424 ± 8 P	423 ± 6 P
4/D/97	relic	microlithon	L3 WNW–ESE	strong cren	–	415 ± 10 M	465 ± 8 P
5/D/97	relic	pen + weak C″	L2 WNW–ESE	–	–	–	435 ± 7 Y

Sample	S1	S2	S3	2–6 µm age	6–11 µm age
North Varanger Region					
6/D/97	relic	pen	very strong	444 ± 12 P	442 ± 4 P
7/D/97	relic	pen	–	456 ± 4 M	–
8/D/97	relic	pen	weak	450 ± 6 M	470 ± 3 M

Errors quoted are 1σ plus a further ± 0.4% on the J value.

Note that deformation histories given here are based solely on criteria found within each individual sample. Relic: seen in S2 microlithons; pen: penetrative fabric; C″: shear band; microlithon: seen in S3 microlithons; cren: crenulation; P: plateau age; M: mean age of several steps combined; Y: age of youngest step in saddle.

rather than the S2 observed in thin section (and as given in Table 2). However, since the rock is mylonitic, it is possible that all evidence of the earliest fabric has been eradicated; the age determined is consistent with this interpretation.

Interpretation of the North Varanger Region results is more uncertain, due to the limited data. Total gas ages range between 454 and 483 Ma, overlapping with the Tanahorn Nappe data. Although the rocks suffered a slightly lower grade of metamorphism than the Tanahorn Nappe, no evidence of a detrital component is seen in the high temperature steps, the ages of which lie within the Finnmarkian to inter-Finnmarkian–Scandian range (Fig. 4). Only fractions from sample 6/D/97, which has a very strongly developed S3 fabric, gave plateaux, at 444–442 Ma (58–71% evolved gas), an inter-Finnmarkian–Scandian age. The plateau ages thus probably reflect the age of the S3 cleavage. In contrast, samples 7/D/97 and 8/D/97 do not show plateaux and the high temperature steps reach 494 Ma. In both these samples, there is textural evidence of a pre-main cleavage (which is S1 in the literature) deformation event, but, critically, evidence of S3 is weak or absent. Consequently, the main cleavage is constrained to be older than the oldest mean age of combined steps (470 Ma).

There is, therefore, an indication that early penetrative deformation within the North Varanger Region was a Finnmarkian event, contemporary with emplacement of the Kalak Nappe Complex. This is consistent, within the very large error, with the Rb–Sr whole-rock cleavage age of 520 ± 47 Ma (MSWD 1.35) from eastern Varangerhalvøya (Taylor and Pickering, 1981; Fig. 1). Note, however, that no Scandian ages were obtained from either mean combined steps or from an individual heating increments, although Scandian reactivation occurred in the Tanahorn Nappe. Thus Scandian dextral displacement of the North Varanger Region must have been accommodated along the Trollfjorden–Komagelva Fault by localised brittle deformation.

Some samples clearly show markedly young ages in the higher temperature steps, down to 361 Ma (sample 3/D/97), possibly due to gas being evolved from other phases, notably chlorite. However, although this process *could* have affected the high temperature steps in all samples, this is thought to be unlikely for two reasons. First, samples not containing significant amounts of chlorite (e.g. sample 2/D/97) do not show older ages in the high temperature steps and, second, the ages determined from most high temperature steps are coincident with the early Caledonian period, which is most unlikely. If some high temperature steps still retained clearly pre-Caledonian ages, this argument would be more likely to apply.

5.2. Comparison with previous data

Sturt et al. (1978) presented a 492 ± 45 Ma Rb–Sr whole-rock age for the penetrative S1 cleavage in the Laksefjord Nappe (Fig. 1). ^{40}Ar/^{39}Ar whole-rock data from the same locality gave a mean combined age at 494 ± 4 Ma, using 53% evolved gas (sample N8; Table 3; Dallmeyer et al., 1989). At other localities in the Laksefjord Nappe, mean ages of combined steps gave inter Finnmarkian–Scandian ages, with minor pre-Caledonian detrital components (Table 3). Dallmeyer et al. (1989) described these results as disturbed data related to gas release from different minerals. Analyses of the 1–2 μm fraction suffered from recoil and do not constrain the age of Caledonian orogenesis, but K–Ar whole-rock and fine fraction data of sample N8 gave Caledonian ages, with finer fractions giving younger ages (Dallmeyer et al., 1989). However, although finer fractions may yield younger ages (Reuter and Dallmeyer, 1987), it not necessarily the case that the youngest age determined constrains the age of a geological event, since closure temperatures are grain size-dependent. The 4–8 μm fraction of sample N8 gave a K–Ar age of 490 ± 11, similar to the ^{40}Ar/^{39}Ar whole-rock combined step age (Table 3, Fig. 4; Dallmeyer et al., 1989) and the Rb–Sr whole-rock age of Sturt et al. (1978).

Dallmeyer et al. (1989) also analysed samples from the Gaissa Thrust Belt (samples N1–5; Figs. 1 and 5), from external (Laksefjord–Tanafjord) and internal areas (Porsangerfjord). The external area underwent diagenetic to anchizone peak metamorphism, whilst the internal area was altered at upper anchizone/epizone conditions (Rice et al., 1989a). Maximum temperatures were, therefore, below the white-mica closure temperature interval. Fold axes trend NE–SW in both areas, in contrast to typical NNE–SSW axial trends in the belt (Townsend et al., 1986). Mean ages from combined steps of ^{40}Ar/^{39}Ar whole-rock data

Table 3
Selected ^{40}Ar/^{39}Ar and K–Ar data from the Laksefjord Nappe and Gaissa Thrust Belt (adapted from Dallmeyer et al., 1989; localities N1–N9 shown in Fig. 1)

^{40}Ar/^{39}Ar whole-rock data

Sample	Unit	Locality	TGA	*MA*	%Gas	Steps	Young	%Gas	Old	%Gas
N2	Gaissa TB.	Vestertana	521.3 ± 9.8	*494.6 ± 3.3*	48	3–4	493.7 ± 2.7	23	795.2 ± 6.5	2
N4	Gaissa TB.	Porsangerfjord	482.1 ± 8.6	*475.4 ± 4.2*	82	3–6	470.1 ± 1.4	25	690.3 ± 2.9	3
N5	Gaissa TB.	Porsangerfjord	473.8 ± 8.6	*466.2 ± 4.9*	56	4–6	460.8 ± 1.3	14	608.1 ± 2.0	6
N6	Laksefjord N.	Ifjord	508.6 ± 10.2	*468.3 ± 4.1*	40	7–9	465.6 ± 1.5	23	645.4 ± 2.2	17
N7	Laksefjord N.	Ifjord	535.4 ± 8.7	*488.4 ± 5.0*	38	4–5	477.9 ± 1.9	6	1030.0 ± 10.8	3
N8	Laksefjord N.	Friarfjord	484.6 ± 9.2	*494.2 ± 4.0*	53	7–9	463.1 ± 2.3	21	716.2 ± 7.3	2
N9	Laksefjord N.	Tarnvik	491.5 ± 8.8	*458.9 ± 11.3*	31	1–3	454.3 ± 2.3	9	605.0 ± 2.7	3

K–Ar data

Sample	Unit	Locality	Grain size (μm)	K–Ar age
N5	Gaissa TB.	Porsangerfjord	< 0.5	440.2 ± 9.4
N5	Gaissa TB.	Porsangerfjord	4–8	496.8 ± 10.9
N5	Gaissa TB.	Porsangerfjord	whole-rock	487.6 ± 10.6
N8	Laksefjord N.	Friarfjord	< 0.5	459.5 ± 11.4
N8	Laksefjord N.	Friarfjord	4–8	490.3 ± 10.8
N8	Laksefjord N.	Friarfjord	whole-rock	504.5 ± 11.5

MA: mean age for combined steps; young: age of youngest step in saddle; old: age of oldest high temperature step.

from the west show early Caledonian ages, defined by up to 82% of the gas evolved (Table 3). ^{40}Ar/^{39}Ar analyses of the 1–2 μm size fraction were affected by excess Ar/recoil, but no high temperature, detrital component is seen. These results were also attributed to gas release from different minerals and taken to be inconclusive by Dallmeyer et al. (1989). K–Ar analysis of the 4–8 and < 0.5 μm fractions and the whole-rock, from sample N5 gave a range of early to mid-Caledonian results. The 4–8 μm fraction, a size range similar to those used in the present study, gave a K–Ar whole-rock age of 497 Ma.

In the data from east Finnmark, a detrital component is present in the whole-rock ^{40}Ar/^{39}Ar spectra, but the mean of combined steps gives an age of 495 Ma in sample N2 (48% gas; Table 3). Recoil/excess argon disturbed the 1–2 μm fraction. Although the isotopic data in the east are inconclu-

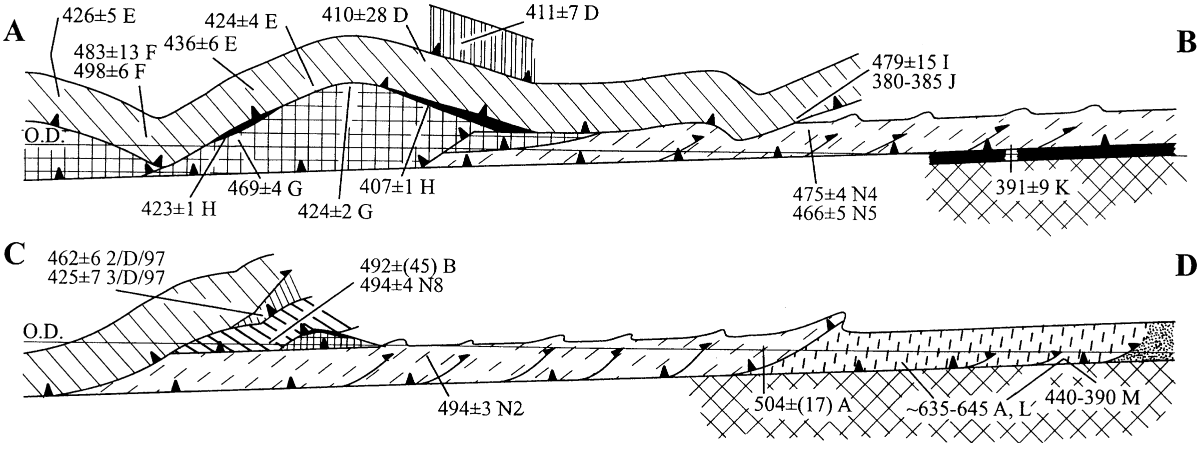

Fig. 5. Schematic geological profile, with isotopic data as in Fig. 1 added. See Fig. 1 for lines of sections. Ages in Ma.

sive, Bylund (1994b) postulated an Ordovician palaeomagnetic component in the rocks east of Tanafjord and south of the Trollfjorden–Komagelva Fault.

Based on Reuter and Dallmeyer (1987)'s observation of strong correlation between grain size and determined age, Dallmeyer et al. (1989) argued that detrital contamination was pervasive in all grain sizes they measured. The youngest K–Ar age (440 Ma) from the finest fraction was thus inferred to provide only an upper constraint on the cleavage age in the Gaissa Thrust Belt. Hence the possibility of Finnmarkian deformation was rejected, even though no or little evidence of a detrital mica ages is present in the K–Ar data in some samples or in the 1–2 μm fraction ^{40}Ar/^{39}Ar data. The interpretation favoured here is one of Finnmarkian resetting of fine grain sizes during D1, followed by partial Scandian overprinting. Such a sequence of events is not remarkable for the Laksefjord Nappe, considering its strong SE-directed ductile deformation (Milton and Williams, 1981). However, for the Gaissa Thrust Belt, such deformation is more difficult to account for, since only Scandian ages have been recorded in the more internal Komagfjord Antiformal Stack (Dallmeyer et al., 1988). However, the NE–SW oriented folds in the parts of the Gaissa Thrust Belt from where the samples were collected also indicate SE-directed deformation, typical of early Caledonian deformation (cf. Townsend, 1987; Roberts and Sundvoll, 1990).

The results obtained from Varangerhalvøya indicate that the evolution of the northern Scandinavian Caledonides should be reassessed, to include Finnmarkian to inter Finnmarkian–Scandian deformation in the footwall of the Kalak Nappe Complex in the North Varanger Region and probably also in the Laksefjord Nappe and Gaissa Thrust Belt. In the areas studied, there was a structurally penetrative, peak metamorphic early event, in which fine-grained white micas were isotopically reset, and a subsequent structural crenulation overprint with partial isotopic resetting. That these can be recognised suggests that the grain sizes measured were the most suitable ones for the type of rocks analysed. Upper anchizone to mid- to lower greenschist facies metamorphism, although unable to completely reset large detrital grains, can more successfully reset grains in the 2–11 μm size range, which is relatively free of recoil/excess argon effects. This can be tested by analysing coarser fractions to establish their detrital component.

The earlier ^{40}Ar/^{39}Ar study of Dallmeyer et al. (1989) used the whole-rock and the 1–2 μm grain size fraction and thus the analyses fell between the Scylla of detrital contamination and the Charybdis of recoil/excess argon. The Laksefjord Nappe and Gaissa Thrust Belt need to be critically reexamined, at both fine and coarser grain sizes, before the model outlined above can be properly evaluated.

6. Conclusions

(1) The similarity of spectra obtained from the 2–6 and 6–11 μm grain size fractions in the present study strongly suggests that no significant detrital material remains in the samples. Similarly, no evidence of the pre-800 Ma Porsanger Orogeny is seen in the data. The ages obtained reflect grain growth during the Caledonian orogeny.

(2) In the mid- to lower greenschist facies Tanahorn Nappe (base Kalak Nappe Complex), a penetrative cleavage (S2) formed at ∼ 460 Ma, during the last stages of the SE-directed Finnmarkian event. This was variably overprinted during the Scandian phase, during E- to ESE-directed deformation (D3; 425 Ma).

(3) The epizone grade North Varanger Region seems to have been affected by late Finnmarkian (D1–D2, pre-470 Ma) to inter-Finnmarkian–Scandian (D3; ∼ 443 Ma) events. Later (?)Scandian deformation must have been restricted to brittle movement along the Trollfjorden–Komagelva Fault. However, microstructural work revealed a more complex structural history than previously envisaged, which needs to be studied in more detail.

(4) Reassessment of published data suggests that Finnmarkian deformation occurred in the Laksefjord Nappe and the trailing part of the Gaissa Thrust Belt. These units need to be re-investigated, using grain sizes less affected by recoil and detrital material.

(5) Altogether, the data rather break down the notion of two discrete phases of deformation—with late Finnmarkian events persisting until ∼ 460 Ma in

the Tanahorn Nappe, strong crenulation deformation occurring at ca. 443 Ma in the North Varanger Region and Scandian deformation occurring at 425 Ma. This agrees with the observations of Page (1992), Sturt and Ramsay (1994) and Andersen et al. (1998).

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Appendix A. Sample preparation and machine conditions

The samples were broken into small blocks, washed and checked that no veins or weathered surfaces were present. They were then initially crushed in a jaw crusher followed by further grain size reduction in a rotational disc crusher. Grain size fractions were separated with Atterberg cylinders. Two grain sizes were separated and measured: 2–6 and 6–11 μm.

The separates (3–10 mg) were enclosed in high purity quartz vials and irradiated at the Nuclear Reactor Centre in Siebersdorf, Austria (now closed). After a >4-week cooling period, the samples were placed in small, annealed (low blank) cylindrical tantalum capsules. For Ar extraction, the RF-heating method was used; the extraction furnace is made from quartz glassware in a Pyrex envelope glass. The hot portion of the extraction furnace is double-walled and this volume was continuously pumped to avoid diffusion from ambient air during the high temperature steps. After finishing the analysis, the sample capsule was dropped out, so that only one capsule lies horizontally in the heating position. The design guaranteed a uniform temperature distribution in the sample, which was monitored by a calibrated pyrometer. The heating period was 10 min for the low temperature steps and was gradually lowered to 3 min for the highest temperature step. Between the heating procedures, the RF was switched off and no gas was released. Cleaning of the gas was done by a combination of cold trap and SAES getters. Two thirds of the gas was introduced into the mass spectrometer, a VG-5400 model from Fisons Isotopes (Winsford, GB); the rest was pumped off. The line and mass-spectrometer are fully automated.

Isotopic ratios are determined from a measuring period of 10 min, representing the ratio at the time of sample inlet. Age calculation was done after corrections for mass discrimination and radioactive decay, especially of the ^{37}Ar, using the formulas given in Dalrymple et al. (1981) and McDougall and Harrison (1999). The K/Ca ratio was determined from the ^{39}Ar/^{37}Ar ratio (calculated for the end of irradiation) using a conversion factor of 0.247. This factor was determined from a plagioclase with uniform and well-known composition.

The ^{40}Ar blank line blank at 1000 °C is approximately 1×10^{-15} mol, the ^{40}Ar/^{36}Ar ratio of the line blank was similar to air composition. The long-term leakage rate of the line is 2×10^{-15} mb l s^{-1}. Interference of ^{36}Ar, ^{37}Ar and, partly, ^{39}Ar with a low background of hydrocarbon radicals in the mass spectrometer can be a limiting factor for reliable measurements of very low intensities. An efficient cleaning procedure is essential and carefully checked peak positions, background determination and corrections (if necessary) are routinely performed to overcome such difficulties. ^{40}Ar and ^{39}Ar were measured on a Faraday detector with a 10^{11} Ω resistance. ^{36}Ar, ^{37}Ar and, partly, ^{39}Ar were recorded on a Daly multiplier with a gain of 100 ± 5%.

J values were determined from an internal laboratory standards, calibrated by international standards, including the muscovite Bern 4M (Burghele, 1987), amphibole Mm1Hb. (Samson and Alexander, 1987) and Fish Canyon sanidine. The errors given on the calculated age of an individual step include only the 1σ error of the analytical data. The errors of the plateau ages or total gas ages include an additional error of ± 0.4% on the J value. Within these latter errors, the age results are reproducible with the same analytical equipment. Inter-laboratory reproducibility can be expected within 1–1.5%.

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