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Chronology of eclogite retrogression within the Seve Nappe Complex, Råvvejaure, Sweden: evidence from $^{40}Ar/^{39}Ar$ mineral ages

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With 6 figures and 4 tables

Zusammenfassung

Die Amphibolitkonzentrate aus vier Proben unterschiedlich regressiver Eklogite aus der Tsäkkok-Linse des Seve-Deckenkomplexes spiegeln diskordante $^{40}Ar/^{39}Ar$ Altersspektren wieder. Diese deuten an, daß eine Argonkontamination von außen stattgefunden hat. $^{36}Ar/^{40}Ar$ gegen $^{39}Ar/^{40}Ar$ Isotopen sind für zwei Proben genau bestimmt und liefern Alter von 464,7 ± 1,3 Mio. und 463,2 ± 6,3 Mio. Jahre. Inverse Ordinatenabschnitte sind sehr viel größer als 295 und bestätigen erhebliche Argon-Fremdkomponenten. Zwei Hellglimmerkonzentrate aus metasedimentären Einheiten der Tsäkkok-Linse zeigen intern konkordante $^{40}Ar/^{39}Ar$ Altersspektren, welche Plateaualter von 448,2 ± 1,6 Mio. und 468,4 ± 0,9 Mio. Jahre besitzen. Ein Amphibolkonzentrat aus einem metamorphen basischen Gang innerhalb der Sarek-Linse des Seve-Deckenkomplexes liefert ein Isotopenkorrelationsalter von 463,8 ± 12,3 Mio. Jahre, welches eine postmetamorphe thermale Entwicklung andeutet, die ähnlich der Tsäkkok-Linse ist. Die Amphibol- und Hellglimmeralter werden dahingehend interpretiert, daß sie die postmetamorphe thermale Abkühlung durch entsprechende Temperaturen für das intrakristalline Zurückhalten des Argons datieren, die im Anschluß an die Amphibolitfaziesregression der Eklogitfaziesvergesellschaftung folgte. Der Seve-Deckenkomplex scheint aus einer distalen Fazies spätprotero- bis frühpalaeozoischen Miogeosynklinale von Baltika hervorgegangen zu sein. Die jetzigen $^{40}Ar/^{39}Ar$ Ergebnisse liefern eine Aufzeichnung von frühpaleozoischen (Vor-Mittelordovizium) tektono-thermalen Aktivitäten, und sie sind daher vergleichbar mit früheren Vermutungen von einer bedeutenden frühkaledonischen Orogenese innerhalb der skandinavischen Kaledoniden.

Abstract

Amphibole concentrates from four samples of variably retrogressed eclogite from the Tsäkkok Lens of the Seve Nappe Complex display discordant $^{40}Ar/^{39}Ar$ age spectra suggestive of extraneous argon contamination. $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlations are well-defined for two samples and yield ages of 464.7 ± 1.3 Ma and 463.2 ± 6.3 Ma. Inverse ordinate intercepts are very much larger than 295 and confirm significant extraneous argon components. Two white mica concentrates from metasedimentary units of the Tsäkkok Lens display internally concordant $^{40}Ar/^{39}Ar$ age spectra which define plateau ages of 448.2 ± 1.6 Ma and 468.4 ± 0.9 Ma. An amphibole concentrate from a metamorphosed basic dike within the Sarek Lens of the Seve Nappe Complex yields an isotope correlation age of 463.8 ± 12.3 Ma, suggesting a post-metamorphic thermal evolution similar to that of the Tsäkkok Lens. The amphibolite and white mica ages are interpreted to date post-metamorphic cooling through appropriate temperatures for intracrystalline retention of argon following amphibolite facies retrogression of the eclogite facies assemblages. The Seve Nappe Com-

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plex appears to have originated within distal facies of the late Proterozoic-early Paleozoic miogeocline of Baltica. The present $^{40}Ar/^{39}Ar$ results provide a record of early Paleozoic (pre-Middle Ordovician) tectonothermal activity and therefore are compatible with previous suggestions of significant early Caledonian orogenesis within the Scandinavian Caledonides.

Résumé

Les concentrés d'amphiboles de quatre échantillons d'éclogites, rétromorphosés à des degrés divers, provenant de la lentille de Träkkok («Seve Nappe Complex») montre un spectre discordant d'âges $^{40}Ar/^{39}Ar$, ce qui suggère une contamination par un apport d'argon. Les corrélations entre $^{36}Ar/^{40}Ar$ et $^{39}Ar/^{40}Ar$ sont bien définies pour deux échantillons et fournissent des âges de 464,7 ± 1,3 Ma et 463,2 ± 6,3 Ma. Les rapports $^{40}Ar/^{36}Ar$ sont beaucoup plus élevés que 295 et confirment un apport extérieur d'argon significatif. Deux concentrés de mica blanc provenant des unités métasédimentaires de la lentille de Tsäkkok présentent des spectres d'âges $^{40}Ar/^{39}Ar$ concordants, qui définissent des âges-plateau de 448,2 ± 1,6 Ma et 468,4 ± 0,9 Ma. Un concentré d'amphibole provenant d'un dyke basique métamorphisé dans la lentille des Sarek du «Seve Nappe Complex» fournit par corrélation isotopique un âge de 463,8 ± 12,9 Ma, ce qui suggère une évolution thermique post-métamorphique similaire à celle de la lentille de Tsäkkok. Les âges fournis par les amphiboles et les micas blancs sont interprétés comme correspondant au refroidissement post-métamorphique, à travers des températures permettant la rétention intracristalline de l'argon, à la suite de la rétromorphose des éclogites dans le faciès des amphiboles. Le «Seve Nappe Complex» a dû être engendré dans les faciès distaux du miogéosynclinal tardi-protérozoïque à éo-paléozoïque de la Baltique. Les valeurs actuelles de $^{40}Ar/^{39}Ar$ enregistrent l'activité tectonothermique du Paléozoïque inférieur (pré-Ordovicien moyen); elles sont donc en accord avec l'hypothèse antérieurement émise d'une orogenèse éo-calédonienne au sein des Calédonides scandinaves.

Краткое содержание

Концентраты амфиболитов из четырех проб эклогитов из линзы Tsäkkok покровного комплекса Seve, подвергшихся регрессивным процессам различной степени, отображают дискордантные спектры возраста с помощью определения его методом $^{40}Ar/^{39}Ar$. Это указывает на то, что здесь имело место загрязнение аргоном из-вне. Точное определение значений $^{36}Ar/^{40}Ar$ и $^{39}Ar/^{40}Ar$ указало на возраст в 464,7 ± 1,3 Мио, и 463,2 ± 6,3 мио. Инверсные отрезки ординат значительно выше 295 и подтверждают, что здесь внесены значительные количества чужеродного аргона. Два концентрата светлой слюды из метаседиментов линцы Tsäkkok проявляют на изохронной диаграмме с конкордией значения соотношения изотопов аргона, дающих возраст 448,2 ± 1,6 и 468,4 ± 0,9 мио. Концентрат амфиболитов из метаморфной основной жилы в линзе Sarek покровного комплекса Seve указал на возраст в 463,8 ± 12,3 мио., что говорит о постметаморфном термальном происхождении, сходным с таковым линзы Tsäkkok. Возраст, полученный по амфиболитам и светлым слюдам, обьясняют тем, что эти минералы при постметаморфическом термальном охлаждении сохранили внутрикристаллиновый аргон и это привело при регрессии амфиболитовой фации к присоединению эклогитовой фации. Покровный комплекс Seve, как кажется, развился из дистальных фаций поздне-протерозойской до раннепалеозойской миогеисинклинали Балтики. Полученные значения $^{40}Ar/^{39}Ar$ указывают на тектоно-термическую активность в раннем палоезое, т.е. до среднего ордовика. Поэтому их можно сопоставлять с предполагаемыми ранее значениями раннего каледонского орогенеза в скандинавских Каледонидах.

Introduction

The structure of the Scandinavian Caledonides is dominated by a sequence of thrust nappe complexes. These were emplaced onto the Baltoscandian platform during early to middle Paleozoic closure of the Iapetus Ocean which culminated in collision of the continents Baltica and Laurentia (e.g., HARLAND & GAYER, 1972; STEPHENS & GEE, 1985). The nappes are of varying metamorphic grade and display marked differences in the complexity of internal deformation. As a result, correlation of specific metamorphic, deformational, and thrusting events along the length of the orogen has been uncertain and controversial (e.g., ROBERTS & GEE, 1985).

This report includes new $^{40}Ar/^{39}Ar$ ages for amphibole in retrograde selvages developed from eclogite assemblages within allochthonous rocks of Baltoscandian affinities exposed in southern Norrbotten, Sweden (Figs. 1 and 2). These results bear directly on both the chronology and nature of Caledonian orogenesis, and provide controls for understanding the early to middle Paleozoic tectonothermal evolution of the Baltoscandian miogeocline.

Geologic setting of the study area

The Scandinavian Caledonides may be described in terms of several major tectonic units (KULLING in Strand & Kulling, 1972; GEE & ZACHRISSON, 1979; ROBERTS & GEE, 1985), including: 1) autochthonous and parautochthonous sequences; 2) Lower, Middle, Upper, and Uppermost Allochthons; and, 3) neoautochthonous, molasse deposits of Early to Middle Devonian age (Figs. 1 and 2). The entire nappe sequence was affected by regional north-south folding following structural emplacement onto the Baltoscandian platform. The overall tectonostratigraphy of the central Scandinavian Caledonides has been treated at length elsewhere (e.g., DYRELIUS et al., 1980; STEPHENS et al., 1985; ROBERTS & GEE, 1985) and will not be reviewed here. Only those relationships particularly relevant to interpretation of the present geochronological results from the Upper Allochthon will be discussed.

The Upper Allochthon is an extremely heterogeneous, internally imbricated structural complex. Basal tectonic units are composed of a westward thinning, up to 5 km thick assemblage of thrust sheets

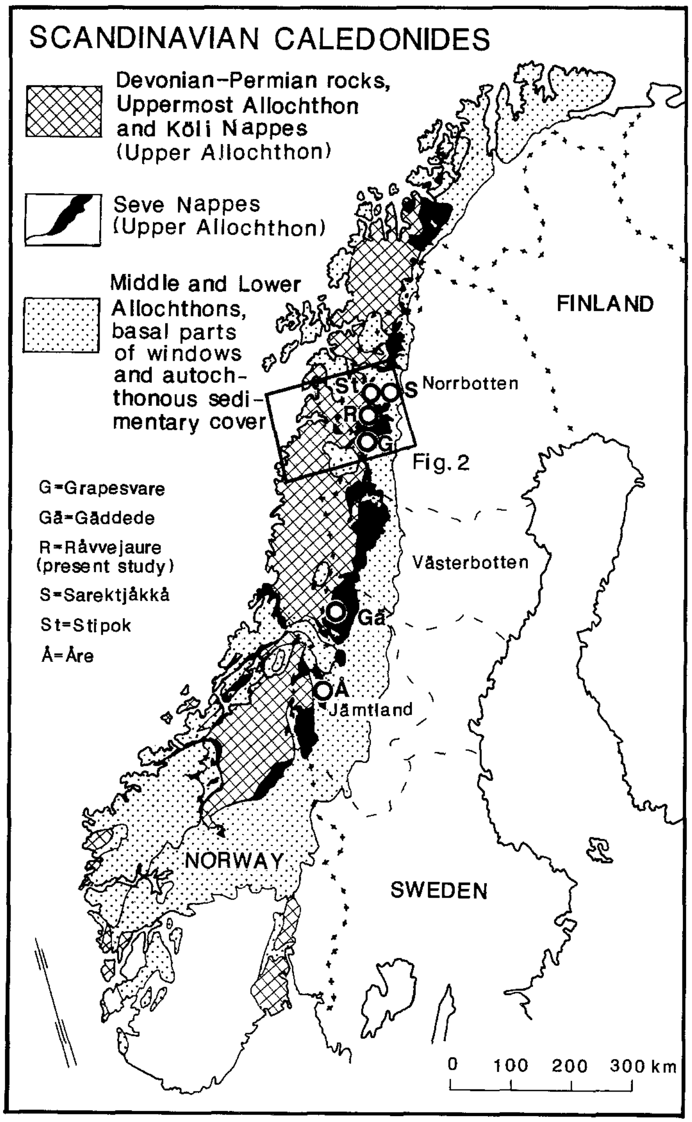

Fig. 1. Regional extent of the Seve Nappe Complex within the Scandinavian Caledonides (adapted from KULLERUD et al., 1990). Area of Figure 2 is outlined.

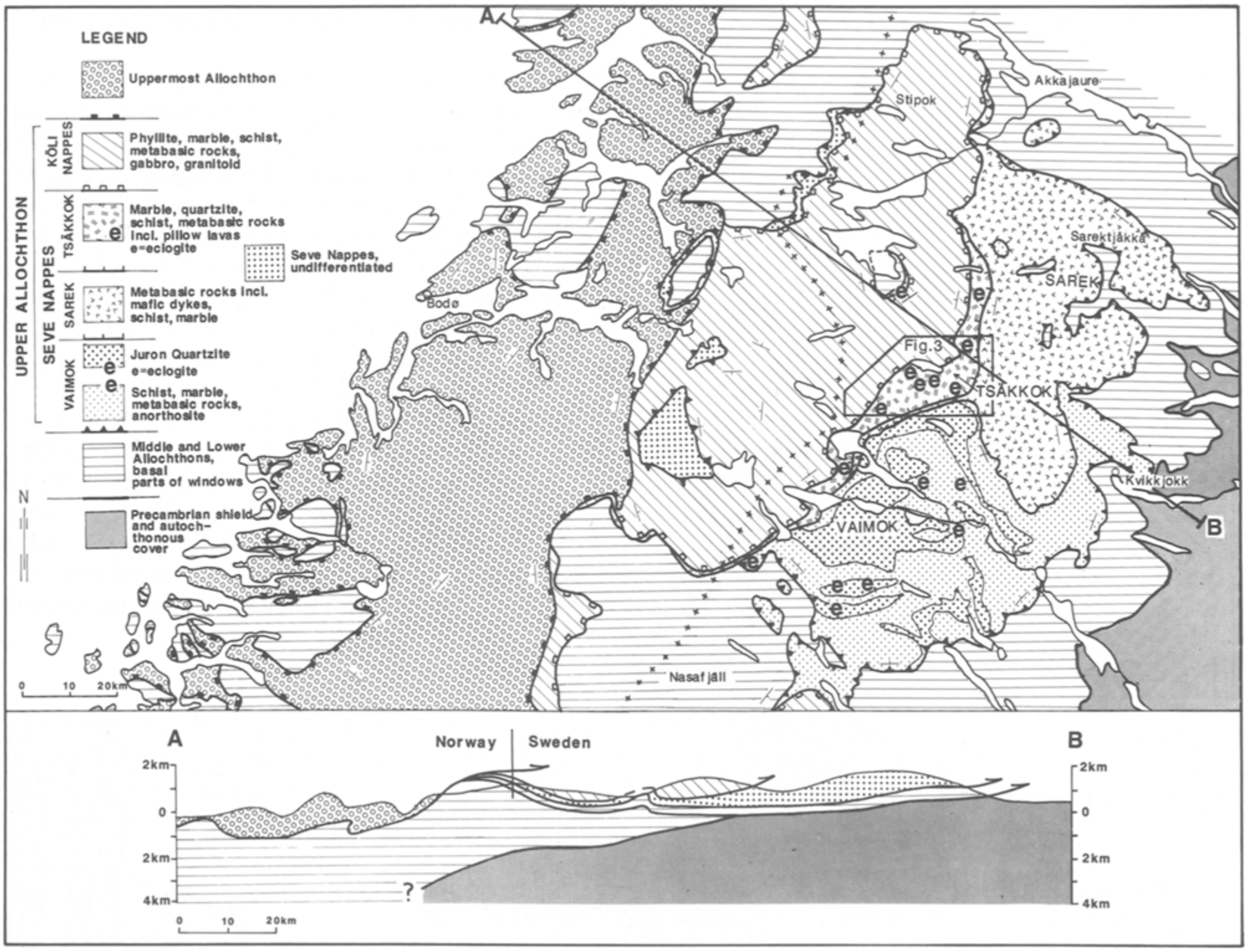

Fig. 2. Tectonostratigraphy in the north-central Scandinavian Caledonides. Area of Figure 3 is outlined.

referred to as the Seve Nappe Complex (e.g., ZACHRISSON, 1969, 1973; TROUW, 1973; ZWART, 1974). This complex consists largely of medium-grade metasedimentary and basic metaigneous units which are locally in tectonic contact with high-grade paragneisses. Tectonic contacts between various structural units within lower portions of the Upper Allochthon are locally marked by development of high-temperature ductile shear zones (e.g., TROUW, 1973; SJÖSTROM, 1983). Variably retrogressed eclogites have been described from several structural units of the Seve Nappe Complex (e.g., VAN ROERMUND & BAKKER, 1984; STEPHENS & VAN ROERMUND, 1984; VAN ROERMUND, 1985; ANDREASSON et al., 1985; SANTALLIER, 1988).

In the southern Norrbotten, ZACHRISSON and STEPHENS (1984) divided the Seve Nappe Complex into the Vaimok, Sarek and Tsäkkok tectonostratigraphic lenses which are dominated by quartz-rich metasedimentary rocks and subordinate metabasic igneous units; marble is conspicuous in the tectonostratigraphically highest Tsäkkok Lens (Figs. 2 and 3). Variably retrogressed eclogite assemblages occur within metabasic rocks of the Vaimok and Tsäkkok Lenses but are conspicuously absent in the tectonostratigraphically intermediate Sarek Lens. Eclogitized pillow lavas with primary contacts to the host metasedimentary rocks have been described from the Tsäkkok unit (KULLERUD et al., 1990).

The overall chemical character of basic rocks within lower portions of the Seve Nappe Complex is similar to that of dolerites in thrust nappe units within the structurally underlying Middle Allochthon (e.g., SOLYOM et al., 1979a, 1979b; ANDRÉASSON et al., 1985; ANDRÉASSON, 1987; KULLERUD et al., 1990). Metasedimentary protoliths in the two tectonic complexes are also comparable. It is therefore likely that the rocks now constituting the Seve Nappe Complex originated in distal, latest Proterozoic to Early Cambrian environments along the continental margin of Baltica (e.g., DALLMEYER & GEE, 1986).

Overlying the Seve Nappe Complex is a succession of predominantly low-to medium-grade metavolcanic and metasedimentary units of the Köli Nappe Complex (ZACHRISSON, 1969; STEPHENS, 1980). Fossil controls demonstrate and U-Pb zircon radiometric age determinations support an Early Ordovician to Early Silurian age for some protoliths. Several Middle Ordovician and younger units within the lowest portions of the Köli Nappe Complex are characterized by lithic successions that can be directly correlated with the Baltoscandian margin (GEE, 1975). Otherwise, the successions appear to be unrelated to Baltica and were apparently derived from a variety of eugeoclinal terranes within the Iapetus Ocean tract (STEPHENS & GEE, 1985, 1989). These exotic units amalgamated and accreted to the Baltoscandian margin during the early to middle Paleozoic.

Tectonothermal evolution of the study area

$^{40}Ar/^{39}Ar$ incremental-release ages have been determined for minerals separated from Seve rocks within the Tsäkkok and Sarek Lenses exposed near Råvvejaure in southern Norrbotten (Figs. 2 and 3). Geologic relationships in the study are have been described by STEPHENS & VAN ROERMUND (1984), KULLERUD (1987) and SNILSBERG (1987). The rocks sampled include variably retrogressed eclogites and host quartz-rich schists in the Tsäkkok Lens and a metamorphosed basic dike in the tectonostratigraphically underlying Sarek Lens.

The eclogites in the Tsäkkok Lens display complex textural relationship which have been described by STEPHENS and VAN ROERMUND (1984), NICHOLSON (1984) and KULLERUD (1987). These workers suggest that basic protoliths initially experienced a medium-grade metamorphism (M_1) which included formation of green amphibolite (ferroan pargasite),

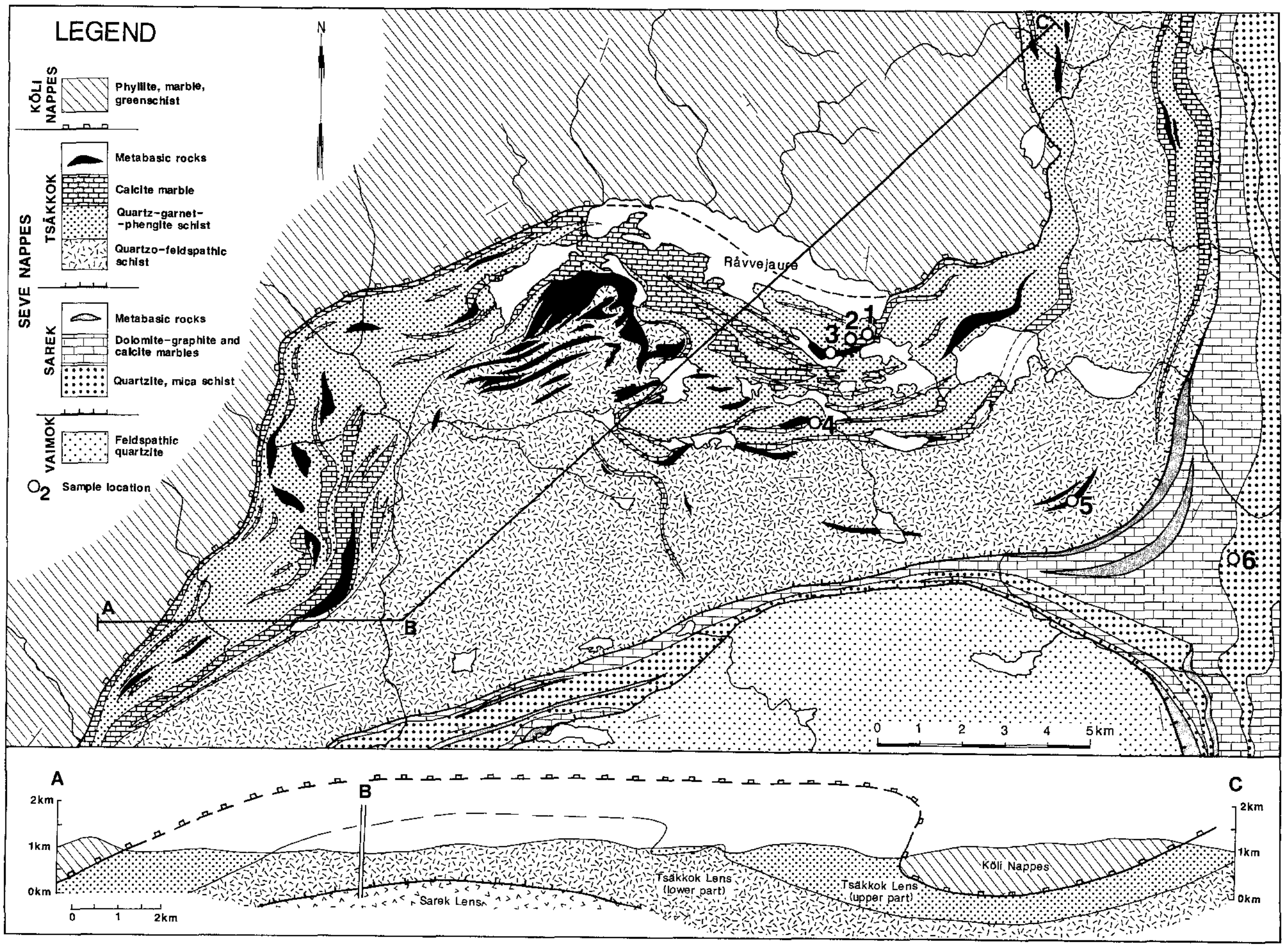

Fig. 3. Generalized geologic map of the Råvvejaure area (adapted from KULLERUD et al., 1990). Locations for which samples were collected for $^{40}Ar/^{39}Ar$ analysis are indicated with numbers.

paragonite, quartz and rutile. During regional prograde metamorphism (M_2) minerals were largely transformed into eclogite assemblages which include glaucophane, crossite, garnet (up to 40 mol percent pyrope), clinopyroxene (up to 50 mol percent jadeite), zoisite, quartz and rutile. Conditions of eclogite formation were estimated by KULLERUD (1987) to have been 500–630 °C and 12–14.5 kb and are generally similar to the earlier estimates of STEPHENS & VAN ROERMUND (1984) and NICHOLSON (1984). MØRK et al. (1988) reported a 505 ± 18 Ma Sm-Nd isochron age (whole-rock + garnet + omphacite) for Tsäkkok eclogite, and interpreted this to date crystallization of the high-pressure assemblage. Subsequent hydrous retrogression of the eclogite assemblages appears to have occurred along a relatively steep P-T trajectory and involved initial growth of porphyroblasts of barroisite and phengite under relatively high P-T conditions and rims of green amphibole (ferroan pargasite) around garnet (KULLERUD, 1987). Later stages of retrogression (M_3) included formation of blue-green amphibole (magnesio- to actinolitic hornblende), symplectitic replacement of clinopyroxene by albite and actinolite, and growth of chlorite, albite and titanite.

The quartz-rich schists which host the eclogites also display a complex metamorphic history (SNILSBERG, 1987). Older assemblages occur as inclusions in porphyroblasts, as relict foliation microlithons and as coarse-grained porphyroblasts. White mica (phengite and locally paragonite), quartz, rutile and locally chloritoid comprise the inclusions and relict foliation microlithons; garnet, phengite, albite and locally chloritoid occur as porphyroblasts. Younger assemblages define a penetrative foliation and have been correlated with the later stages of retrogression (M_3) in the metabasic rocks.

The presence of glaucophane and crossite in the metabasic rocks indicates a low-temperature high-pressure metamorphism (STEPHENS & ROERMUND, 1984) of rocks which appear to have originated within distal portions of the early paleozoic Baltoscandian miogeocline. Samples were collected for $^{40}Ar/^{39}Ar$ analysis to compare with the Sm-Nd crystallization age of the eclogites and thereby provide additional chronologic brackets for the early Paleozoic tectonothermal evolution of the Baltoscandian miogeocline.

Analytical methods

Techniques used during $^{40}Ar/^{39}Ar$ analysis of the Norrbotten samples generally followed those described in detail by DALLMEYER & KEPPIE (1987). Mineral concentrates were irradiated in the central thimble position of the U.S. Geological Survey TRIGA reactor in Denver, Colorado. Variations in the flux of neutrons along the length of the irradiation assembly were monitored with several mineral standards, including MMhb-1 (ALEXANDER & others, 1978). The samples were incrementally heated until fused with an RF generator. Each heating step was maintained for 30 min. Measured isotopic ratios were corrected for the effects of mass discrimination, total-system blank levels, decay of ^{37}Ar, and interfering isotopes produced during irradiation. Apparent $^{40}Ar/^{39}Ar$ ages were calculated from the corrected isotopic ratios using the decay constants and isotopic abundance ratios by STEIGER & JÄGER (1977).

Intralaboratory uncertainties are reported. Interlaboratory uncertainties are c. 1.25–1.5% of the quoted age. A "plateau" is considered to be defined if: 1) ages recorded by two or more contiguous gas fractions each representing > 4% of the total ^{39}Ar evolved (and together constituting > 50% of the total quantity of ^{39}Ar evolved) are mutually similar within a ± 1% intralaboratory uncertainty; and 2) plateau increments have similar apparent K/Ca ratios. Analyses of the MMhb-1 monitor indicate that apparent K/Ca ratios may be calculated through the relationship of 0.518 (± 0.0005) x $^{39}Ar/^{37}Ar$ (corrected).

The analysis of the amphibole concentrates have been plotted on $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlation diagrams. Regression techniques followed the methods of York (1969). The mean square of the weighted deviates (MSWD) has been used to evaluate isotopic correlations.

Results

Five amphibole and two white mica concentrates have been prepared from samples collected within the Tsäkkok and Sarek Lenses in the vicinity of Råvvejaure. Sample locations are shown in Figure 3 and are described in the Appendix. Petrographic descriptions of the samples are also provided in the Appendix. The concentrates have been analyzed using $^{40}Ar/^{39}Ar$ incremental-release techniques. The analytical data are listed in Tables 1 and 3 and are portrayed as age spectra in Figures 4–6. Isotope correlation calculations from the $^{40}Ar/^{39}Ar$ analytical data are listed in Tables 2 and 4. Apparent K/Ca ratios are relatively low and display considerable intrasample variations in the amphibole analyses (Figs.

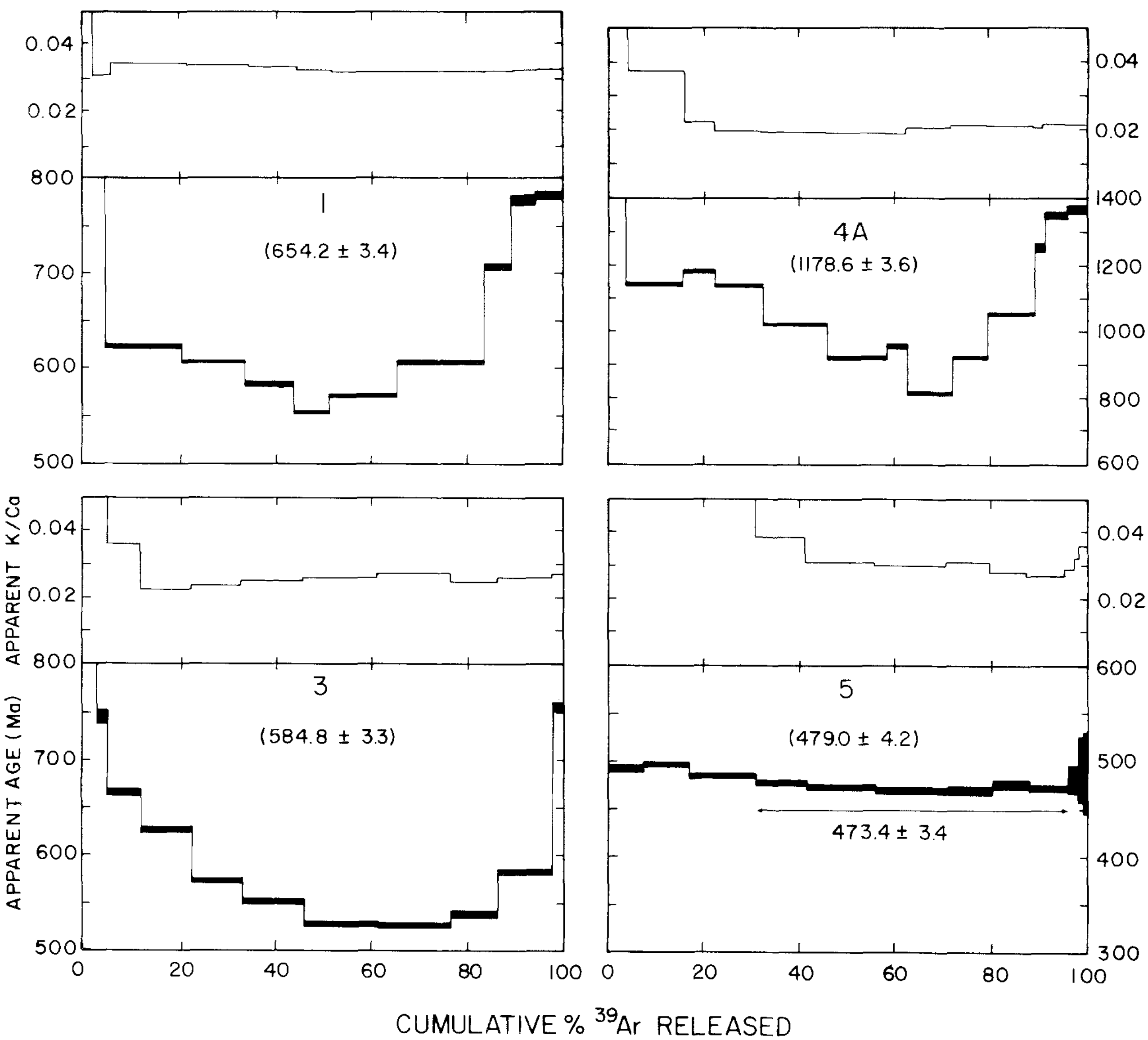

Fig. 4. $^{40}Ar/^{39}Ar$ incremental-release age and apparent K/Ca spectra of amphibole concentrates from the Tsäkkok Lens, Råvvejaure area, Scandinavian Caledonides. Locations shown in Figure 3. Analytical uncertainties (two sigma, intralaboratory) are represented by vertical width of bars. Experimental temperatures increase from left to right. Plateau and/or total-gas (parentheses) ages are listed on each spectrum. Plateau increments delineated with arrows.

4 and 6). Apparent K/Ca ratios are high and show no significant or systematic variations throughout the white mica analyses. Therefore they are not presented with the white mica age spectra in Figure 5.

Tsäkkok Lens

Amphibole

Amphibole concentrates were prepared from four samples of retrogressed eclogite collected within the Tsäkkok Lens (locations 1, 3, 4 and 5; Fig. 3). These display variably discordant age spectra (Table 1, Fig. 4) which define total-gas ages of 654.2 ± 3.4 Ma (1), 584.8 ± 3.3 Ma (3), 1178.6 ± 3.6 Ma (4A) and 479.0 ± 4.2 Ma (5). Low-temperature gas fractions display considerable variation in apparent ages. These are matched by intrasample fluctuations in apparent K/Ca ratios which suggests experimental evolution of argon from compositionally distinct, relatively non-retentive phases. These could be represented by very minor, optically undetectable mineralogic contaminants in the amphibole concentrates and/or petrographically unresolvable exsolution or compositional zonation within constituent

Release temp (^{o}C)	(^{40}Ar/^{39}Ar)*	(^{36}Ar/^{39}Ar)*	(^{37}Ar/^{39}Ar)^{c}	^{39}Ar % of total	%^{40}Ar non-atmos.$^{+}$	^{36}Ar$_{Ca}$ %	Apparent Age (Ma)**
			TSÄKKOK LENS				
Sample 1:	J = 0.008061						
600	1302.22	0.95036	32.790	0.41	78.64	0.94	4047.7 ± 70.2
650	286.65	0.27560	10.443	0.67	71.88	1.03	1772.8 ± 45.1
725	91.01	0.05529	15.980	3.80	83.45	7.86	868.5 ± 6.7
775	54.68	0.01771	14.797	15.91	92.59	22.72	622.3 ± 2.3
800	52.54	0.01556	14.844	13.13	93.51	25.95	606.6 ± 1.4
815	51.09	0.01812	14.973	10.01	91.86	22.47	583.5 ± 3.4
830	48.23	0.01779	15.255	7.52	91.63	23.32	554.3 ± 2.3
850	47.53	0.00989	15.285	14.13	96.42	42.02	571.9 ± 1.9
870	50.35	0.00850	15.244	18.05	97.43	48.78	606.1 ± 1.8
890	61.90	0.01399	15.098	5.84	95.27	29.36	707.2 ± 5.3
910	69.57	0.01427	14.946	5.12	95.66	28.48	780.7 ± 9.1
Fusion	138.76	0.24720	14.902	5.40	48.22	1.64	784.1 ± 7.2
Total	65.56	0.03370	15.125	100.00	91.36	29.34	654.2 ± 3.4
Sample 3:	J = 0.008655						
600	135.99	0.19874	5.312	2.88	57.12	0.73	929.7 ± 4.9
650	91.98	0.11330	4.146	2.17	63.96	1.00	743.7 ± 8.5
700	67.36	0.05839	13.521	6.87	75.99	6.30	666.1 ± 2.9
750	53.96	0.02832	21.578	10.64	87.69	20.72	626.2 ± 3.0
775	46.87	0.01989	20.430	10.19	90.95	27.93	572.6 ± 3.4
810	43.63	0.01454	19.265	13.04	93.69	36.03	552.0 ± 2.6
820	41.45	0.01366	18.478	15.41	93.83	36.78	528.5 ± 2.3
840	41.51	0.01395	17.601	15.15	93.46	34.31	527.2 ± 2.4
860	41.28	0.01049	19.317	9.89	96.24	50.09	538.6 ± 3.8
875	45.22	0.01060	18.440	11.23	96.34	47.33	582.7 ± 3.0
Fusion	63.15	0.01699	17.617	2.53	94.28	28.20	756.3 ± 6.3
Total	50.18	0.02601	18.003	100.00	90.41	32.07	584.8 ± 3.3
Sample 4A:	J = 0.008481						
600	2946.87	0.73847	23.907	1.33	92.66	0.88	5771.2 ± 23.1
650	788.79	0.18728	4.540	2.60	93.03	0.66	3571.4 ± 3.9
725	115.02	0.04367	12.907	11.97	89.68	8.04	1140.6 ± 2.6
750	118.71	0.04450	21.606	6.55	90.38	13.21	1179.1 ± 3.6
775	112.14	0.04337	24.977	9.89	90.36	15.66	1132.1 ± 3.6
800	97.20	0.03830	24.979	13.49	90.42	17.74	1017.0 ± 2.0
820	85.50	0.03590	25.320	12.37	89.96	19.18	917.5 ± 2.9
840	92.04	0.04591	25.510	4.33	87.48	15.11	950.9 ± 3.6
860	71.87	0.02597	23.514	9.52	91.95	24.63	812.4 ± 2.5
875	83.92	0.02938	22.709	7.40	91.82	21.03	917.5 ± 2.1
890	97.38	0.02398	22.775	10.01	94.60	25.84	1052.9 ± 2.4
905	123.22	0.02869	23.290	2.12	94.63	22.08	1253.7 ± 9.1
925	140.07	0.04302	22.334	4.65	92.20	14.12	1347.8 ± 5.2
Fusion	317.55	0.63502	22.478	3.77	41.48	0.96	1366.6 ± 8.6
Total	163.89	0.07229	22.050	100.00	89.23	16.47	1178.6 ± 3.6

Table 1. ^{40}Ar/^{39}Ar analytical data for incremental heating experiments on amphibole concentrates from the Seve Nappe Complex, central Scandinavian Caledonides, Norbotten, Sweden.

Sample 5:	J = 0.008702						
600	46.32	0.03473	0.597	7.65	77.93	0.47	492.9 ± 3.9
650	41.18	0.01607	1.157	9.33	88.68	1.96	498.1 ± 2.7
700	39.24	0.01448	5.542	13.97	90.22	10.41	486.0 ± 2.6
740	38.71	0.01725	12.551	10.39	89.42	19.78	478.4 ± 3.2
775	39.29	0.02152	15.549	14.59	86.98	19.65	473.8 ± 2.6
800	36.29	0.01263	16.050	15.10	93.25	34.56	469.9 ± 3.9
820	36.80	0.01448	15.532	9.28	91.75	29.17	468.7 ± 4.8
840	36.97	0.01348	17.140	7.63	92.93	34.58	476.4 ± 4.3
860	35.51	0.00967	17.874	8.12	95.98	50.26	473.2 ± 3.6
880	37.82	0.01439	16.566	2.10	92.26	31.32	482.8 ± 13.1
900	45.42	0.03978	14.984	1.00	76.76	10.25	482.0 ± 37.1
Fusion	48.09	0.05335	13.485	0.84	69.46	6.88	463.8 ± 25.1
Total	38.87	0.01733	11.735	100.00	89.59	22.06	479.0 ± 4.2
			SAREK LENS				
Sample 6:	J = 0.007825						
600	513.84	0.45327	3.113	0.99	73.98	0.19	2492.1 ± 10.1
650	313.00	0.62721	5.184	0.62	40.92	0.22	1255.4 ± 43.2
725	138.42	0.12125	10.517	2.55	74.72	2.36	1075.1 ± 6.9
750	125.71	0.07796	13.366	1.89	82.52	4.66	1079.0 ± 5.2
775	93.73	0.04989	14.395	4.01	85.50	7.85	884.6 ± 3.5
800	73.09	0.03178	14.666	7.83	88.76	12.55	746.3 ± 2.9
820	64.23	0.02882	14.699	7.08	88.57	13.87	669.5 ± 2.4
840	56.90	0.02812	14.212	6.22	87.39	13.74	597.5 ± 6.7
860	57.76	0.02615	14.287	8.75	88.60	14.86	612.3 ± 2.8
880	61.07	0.02974	14.433	16.50	87.50	13.20	635.1 ± 8.4
900	55.55	0.02380	4.544	36.97	89.43	16.62	597.1 ± 2.9
Fusion	73.11	0.08054	14.424	6.60	69.02	4.87	605.0 ± 3.9
Total	70.97	0.04251	14.193	100.00	86.34	13.23	677.6 ± 4.0

*measured.

ᶜcorrected for post-irradiation decay of ^{37}Ar (35.1 day 1/2-life).

+$[^{40}Ar_{tot.} - (^{36}Ar_{atmos.})(295.5)] / ^{40}Ar_{tot.}$

**calculated using correction factors of Dalrymple et al. (1981); two sigma, intralaboratory errors.

Table 1. Continued (page 2).

amphibole grains. In general, most gas fractions evolved from the Tsäkkok amphibole concentrates at intermediate and high experimental temperatures are characterized by similar intrasample apparent K/Ca ratios, indicating evolution of gas occurred from compositionally uniform populations of intracrystalline sites. However, markedly different apparent age relationships are observed in these portions of the four experiments.

The amphibole concentrate from sample 5 displays the most concordant age spectrum of the four Tsäkkok samples analyzed (Table 1, Fig. 4). The 740–860 °C increments comprise c. 65 % of the total ^{39}Ar evolved and are characterized by similar apparent K/Ca ratios. These six increments record similar apparent ages which define a plateau of 473.4 ± 3.4 Ma. The plateau data yield a well-defined $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlation (MSWD = 0.48: Table 2) with an inverse ordinate intercept of 327.2 ± 13.2. This is slightly higher than the 295.5 $^{40}Ar/^{36}Ar$ ratio in the present-day atmosphere, and suggests that minor extraneous argon is present within constituent amphibole grains. Use of the inverse abscissa intercept ($^{40}Ar/^{39}Ar$) in the

Sample	Isotope Correlation Age (Ma)*	$^{40}Ar/^{36}Ar$ Intercept**	MSWD	Increments Included+	% of Total ^{39}Ar	Calculated $^{40}Ar/^{39}Ar$ Age (Ma)***
			TSÄKKOK LENS			
3	463.2 ± 6.3	556.1 ± 12.3	0.57	750-840	64.43	556.1 ± 3.2
5	464.7 ± 2.2	327.2 ± 13.2	0.48	740-860	65.10	473.1 ± 3.7
			SAREK LENS			
6	463.8 ± 12.3	911.1 ± 63.2	0.11	840-900	68.44	608.3 ± 4.6

* Calculated using the inverse abscissa intercept ($^{40}Ar/^{39}Ar$ ratio) in the age equation.

** Inverse ordinate intercept.

*** Table 1.

\+ °C.

Table 2. $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlations from incremental-heating experiments of amphibole concentrates from the Seve Nappe Complex, central Scandinavian Caledonides, Norrbotten, Sweden.

age equation yields a plateau isotope correlation age of 464.7 ± 1.3 Ma. Because this calculation does not depend upon assumption of a modern-day $^{40}Ar/^{36}Ar$ ratio, it is considered more reliable than the plateau age directly calculated from the analytical data. The 465 Ma age is interpreted to date the last cooling through those temperatures required for intracrystalline retention of argon within constituent amphibole grains. HARRISON (1981) indicated that closure temperatures for argon systems within magmatic hornblende are not significantly affected by compositional variations, and suggested that values of 500 ± 25 °C are appropriate in the range of cooling rates likely to be encountered in most geologic settings.

Samples 1,3 and 4A display discordant spectra (Table 1, Fig. 4) in which apparent ages systematically decrease throughout intermediate-temperature portions of each analysis to an age minimum. Apparent ages systematically increase throughout high-temperature portions of the three analyses. Similar types of "saddle-shaped" discordance in amphibole $^{40}Ar/^{39}Ar$ age spectra have been interpreted by DALLMEYER (1975), HARRISON & MCDOUGALL (1981), DALLMEYER & RIVERS (1983) and DALLMEYER et al. (1985) to reflect experimental liberation of gas with large and variable components of extraneous ^{40}Ar relative to intracrystalline radiogenic ^{40}Ar. The 750–840 °C increments evolved from concentrate 3 (representing c. 64% of the total) yield a well-defined isotope correlation (MSWD = 0.57) corresponding to an age of 463.2 ± 6.3 Ma. An inverse ordinate intercept of 556.1 ± 12.3 confirms the presence of significant extraneous argon components. The 463 Ma age is considered geologically meaningful and is interpreted to date the last cooling through amphibole argon closure temperatures. No statistically meaningful isotope correlations are defined by any combinations of the analytical date from analyses of the amphibole concentrates from samples 1 and 4A. This suggests complex intracrystalline contamination with extraneous argon components. Therefore no geologic significance is affixed to any of the $^{40}Ar/^{39}Ar$ apparent ages recorded by these 2 samples.

White Mica

White mica concentrates from two samples (2 and 4B) of quartz-rich schist collected within the Tsäkkok Lens display internally discordant age spectra (Table 3, Fig. 5) yielding total-gas ages of 447.5 ± 2.5 Ma (2) and 466.8 ± 3.3 Ma (4B). Analytical data from increments representing > 4% of the total from each analysis yield well-defined isotope correlations (Table 4) corresponding to ages of 448.2 ± 1.6 Ma (2) and 468.4 ± 0.9 Ma (4B). The inverse ordinate intercepts are similar to 295.5 and do not suggest the presence of extraneous argon components. The isotope correlation ages are therefore considered geologically significant, and are interpreted to date the last cooling through temperatures required for intracrystalline retention of argon. Although not fully

Release temp (°C)	$(^{40}Ar/^{39}Ar)$*	$(^{36}Ar/^{39}Ar)$*	^{39}Ar % of total	$\%^{40}Ar$ non-atmos.+	Apparent Age (Ma)**
Sample 2: J = 0.008515					
580	54.70	0.08405	0.27	54.72	409.8 ± 27.0
605	39.14	0.01552	1.83	88.31	465.4 ± 6.0
625	35.40	0.00479	4.12	95.96	458.3 ± 3.4
650	35.27	0.00547	7.09	95.43	454.7 ± 3.1
670	34.79	0.00450	10.21	96.15	452.1 ± 1.9
690	34.77	0.00426	11.72	96.35	452.7 ± 1.2
720	34.65	0.00441	10.38	96.24	451.0 ± 1.4
750	34.48	0.00409	12.63	96.46	449.8 ± 1.2
780	34.03	0.00432	10.32	96.25	443.8 ± 2.6
805	33.74	0.00337	13.21	97.02	443.6 ± 2.6
830	33.07	0.00285	11.36	97.44	437.4 ± 2.8
855	32.55	0.00251	5.83	97.75	432.5 ± 4.0
Fusion	34.64	0.00397	1.02	96.96	454.2 ± 11.9
Total	34.38	0.00443	100.00	96.28	447.5 ± 2.5
Sample 4B: J = 0.008335					
580	52.78	0.06580	0.32	63.22	442.8 ± 32.2
610	42.56	0.01362	2.21	90.49	502.2 ± 4.2
630	38.31	0.00503	3.26	96.12	482.9 ± 6.4
660	37.80	0.00675	6.38	94.70	471.0 ± 4.6
700	37.93	0.00778	18.84	93.92	469.0 ± 2.5
750	37.12	0.00478	24.16	96.18	469.9 ± 2.7
810	36.89	0.00455	25.12	96.33	468.0 ± 2.8
860	35.45	0.00418	16.38	96.51	452.6 ± 3.9
Fusion	35.01	0.00409	3.34	96.52	447.7 ± 5.4
Total	37.12	0.00569	100.00	95.53	466.8 ± 3.3

*measured.

+ $[^{40}Ar_{tot.} - (^{36}Ar_{atmos.})(295.5)]/^{40}Ar_{tot.}$

**calculated using correction factors of Dalrymple et al. (1981); two sigma, intralaboratory errors; $^{37}Ar/^{39}Ar$ corrected ratio < 0.020 in all analyses.

Table 3. $^{40}Ar/^{39}Ar$ analytical data for incremental-heating experiments on white-mica concentrates from the Seve Nappe Complex, central Scandinavian Caledonides, Norrbotten, Sweden.

calibrated experimentally, use of the preliminary data of ROBBINS (1972) in the diffusion equations of Dodson (1973) indicates muscovite closure temperatures of c. 400 °C. These are similar to those suggested for muscovite on the basis of empirical comparisons with other mineral isotopic systems (e. g., WAGNER et al., 1977; JÄGER, 1979).

Sarek Nappe

An amphibole concentrate was prepared from a metamorphosed basic dike collected at location 6 within the Sarek Lens. The concentrate displays an internally discordant age spectrum (Table 2, Fig. 6) which defines a total-gas age of 677.6 ± 4.0 Ma. The

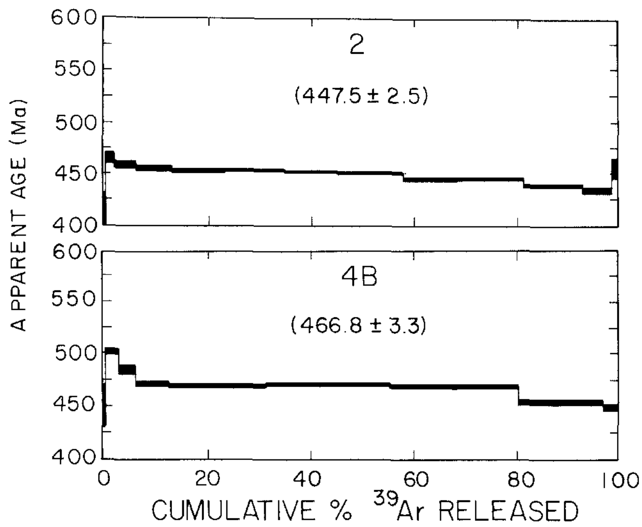

Fig. 5. $^{40}Ar/^{39}Ar$ incremental-release age spectra of white-mica concentrates from the Tsäkkok Lens, Råvvejaure area, Scandinavian Caledonides. Data plotted as in Figure 4.

840–900 °C increments comprise c. 68% of the total gas evolved from the sample and are characterized by similar apparent K/Ca ratios. These four increments correspond to an isotope correlation (MSWD = 0.11: Table 2) which defines an age of 463.8 ± 12.3 Ma. The inverse ordinate intercept is 911.1 ± 63.2 and suggests intracrystalline contamination with extraneous argon.

Geologic significance

Interpreting the geologic significance of the $^{40}Ar/^{39}Ar$ results depends upon calibration of the Ordovician and Silurian time-scales (e.g., Harland et al., 1982; Palmer, 1983). Snelling (1985) suggested that the Ordovician-Silurian boundary (base of the Llandovery) is c. 435–440 Ma. This age together with a 455 Ma calibration of the top of the Middle Ordovician (Kunk et al., 1985) and a 420 Ma calibration for the base of the Ludlow (Wyborn et al., 1982) is used for interpretation of the Seve $^{40}Ar/^{39}Ar$ results from southern Norrbotten.

Amphibole within retrogressed eclogite assemblages from the Tsäkkok Lens and from a metamorphosed basic dike from the Sarek Lens, both occurring in the Seve Nappe Complex of southern Norrbotten, display variable contamination with extraneous argon components. Isotope correlations are

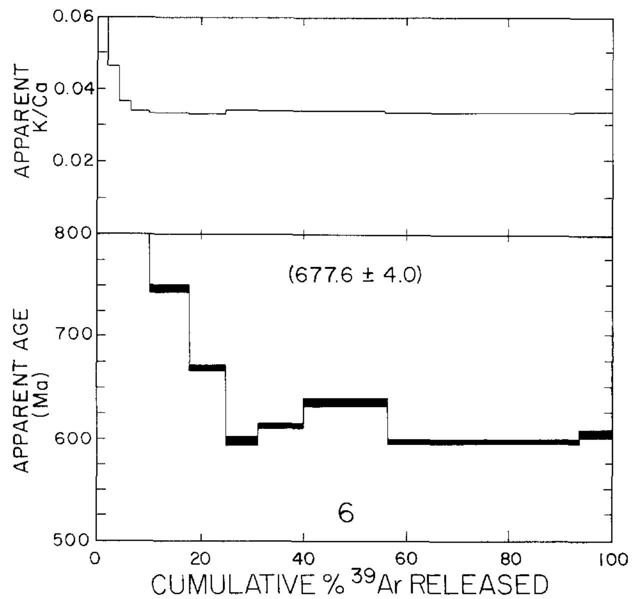

Fig. 6. $^{40}Ar/^{39}Ar$ incremental-release age and apparent K/Ca spectra of an amphibole concentrate from the Sarek Lens, Råvvejaure area, Scandinavian Caledonides. Data plotted as in Figure 4.

Sample	Isotope Correlation Age (Ma)*	$^{40}Ar/^{36}Ar$ Intercept**	MSWD	Increments Included+	% of Total ^{39}Ar	Calculated $^{40}Ar/^{39}Ar$ Age (Ma)***
2	448.2 ± 1.6	308.8 ± 9.3	0.26	625-855	96.88	447.3 ± 2.2
4B	468.4 ± 0.9	305.9 ± 6.3	0.60	660-860	90.87	466.1 ± 3.0

* Calculated using the inverse abscissa intercept ($^{40}Ar/^{39}Ar$ ratio) in the age equation.

** Inverse ordinate intercept.

*** Table 3.

+ °C.

Table 4. $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlations from incremental-heating experiments of white-mica concentrates from the Seve Nappe Complex, central Scandinavian Caledonides.

well-defined for three of the five concentrates analyzed, and yield ages of c. 460–470 Ma. These are interpreted to date the last cooling through appropriate temperatures for intracrystalline retention of argon (c. 500 °C). A relatively rapid post-metamorphic cooling would imply that the c. 460–470 Ma $^{40}Ar/^{39}Ar$ cooling ages should not be significantly younger than initial crystallization of the eclogite assemblages. However, the $^{40}Ar/^{39}Ar$ ages are markedly younger than the 505 ± 18 Ma Sm-Nd crystallization age reported by MØRK et al. (1988) for a Tsäkkok eclogite. This difference in age is consistent with significant interruption of rapid uplift at crustal depths between 20 and 30 Km (KULLERUD, 1987). White mica within the Tsäkkok Lens records c. 448–468 Ma cooling ages suggesting that relatively rapid cooling occurred during final upward movement to shallower crustal levels.

There is no clear record of a distinct Middle Silurian-Early Devonian (Scandian) thermal overprint in the present Seve results. This is surprising because within the study area Seve Nappe units are structurally overlain by the Lower Koli Nappes which contain Late Ordovician, fossil-bearing limestones. Lack of a Scandian thermal overprint in the Seve units examined at Råvvejaure requires relatively high crustal levels for the Seve Nappes during Scandian orogenesis. However, this is consistent with the low-grade character of metamorphism observed in the Lower Koli Nappes in the Råvvejaure area.

Regional tectonic significance

The tectonic history suggested by $^{40}Ar/^{39}Ar$ mineral dates recorded in structural units of the Seve Nappe Complex exposed in the Råvvejaure area, southern Norrbotten is generally similar to the polyorogenic evolution previously outlined for the Seve rocks in several other areas of the central Scandinavian Caledonides; however, there appear to be significant differences in the relative timing of individual tectonothermal events.

In the Gäddede area of northern Jämtland and near Åre in west-central Jämtland (Fig. 1), hornblende within Seve amphibolites has yielded $^{40}Ar/^{39}Ar$ cooling ages of c. 455–475 (DALLMEYER et al., 1985; DALLMEYER & GEE, 1988). At Gäddede, local rejuvenation of the hornblende argon system occurred at c. 430 ± 5 Ma. By contrast, DALLMEYER & GEE (1986) reported older (491 ± 8 Ma) $^{40}Ar/^{39}Ar$ ages for hornblende within retrogressive assemblages developed from eclogites in the Vaimok Lens, Grapesvare area southern Norrbotten (Fig. 1). The $^{40}Ar/^{39}Ar$ hornblende ages from Grapesvare were interpreted to date cooling following the high pressure metamorphism which has been dated at 503 ± 14 Ma using a Sm-Nd mineral (garnet ± omphacite) isochron (MØRK et al., 1988). Further north from the present study area, in the imbricated structural units of the Seve Nappe Complex exposed in the Sarektjåkkå mountains of southern Norrbotten (Fig. 1), the tectonothermal record is even more complex. In this area, hornblende cooling ages fall into distinctive groups at c. 500–520, c. 455–470 and c. 426–435 Ma (DALLMEYER et al., 1991). The c. 460–470 Ma amphibole dates recorded in Seve units within the present study area are in close agreement with the results from Jämtland and with some of the results from Sarektjåkkå. These dates may signify structural imbrication during the same tectonothermal event. In both the Gäddede and Råvvejaure areas, structural units metamorphosed under high- and intermediate-pressure conditions are involved. However, it is clear that there is no simple model for the uplift history of the whole Seve Nappe Complex in the central part of the Scandinavian Caledonides during the early Paleozoic. Different areas and different tectonic segments appear to have attained the crustal level necessary for intracrystalline retention of argon in amphibole at different times.

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Appendix

Locality Descriptions

Locality 1. (27G*, 744935/154775**). Foliated, metabasic rock structurally overlying marble and underlying quartz-mica schist and marble in the upper part of the Tsäkkok Lens. Lithological contacts at this locality are deformed by a mesoscopic, post-schistosity fold. The metabasic rock is c. 1 m thick on the fold limbs and is composed predominantly of blue-green amphibole which displays a hornblende composition (M_3***), epidote, plagioclase feldspar, chlorite and titanite/opaque mineral phases. Plagioclase, epidote and chlorite often occur in small lensoid aggregates up to 2.0 x 0.5 mm.

Locality 2. (27G, 744925/154755). Layered quartzite and quartz-mica schist in the upper part of the Tsäkkok Lens. The quartzite layers are up to 0.5 m thick. The sampled quartz-mica schist contains quartz, plagioclase feldspar, white mica displaying a phengite composition and biotite with subordinate calcite and chlorite. White mica and biotite are oriented oblique to or along the dominant grain-shape fabric.

Locality 3. (27G, 744890/154695). Metabasic rock located close to the southern, structurally lower margin of an eclogite body which locally contains glaucophane and crossite (STEPHENS & VAN ROERMUND, 1984). The metabasic rock is underlain by quartz-mica schist. All units are situated in the upper part of the Tsäkkok Lens. The metabasic rock is coarse-grained and contains amphibole, epidote/clinozoisite, plagioclase feldspar and sphene occasionally situated around opaque mineral phases. Garnet, biotite, chlorite and calcite are subordinate phases. The amphibole is dominantly blue-green in color and displays a hornblende composition (M_3). Some grains are, however, zoned with colorless cores (late M_2-barrosite) and blue-green rims (M_3).

* map-sheet.
** coordinates, national grid-system.
*** metamorphic stage, see text.

Locality 4. (27G, 744735/154660). Metabasic rock (4A) passes transitionally upward into eclogite. This body is structurally underlain by quartz-mica-garnet schist (4B). Both units occur in the upper part of the Tsäkkok Lens. The metabasic rock (4A) is coarse-grained and foliated. It is dominated by a matrix containing zoned amphibole with colorless cores (late M_2-barrosite) and blue-green rims (M_3-hornblende), and sphene situated around opaque mineral phases. This matrix encloses aggregates up to 1 mm across of chlorite + epidote/clinozoisite + plagioclase feldspar + biotite with occasional relics of garnet. Sample 4B contains quartz, white mica displaying a phengite composition, biotite, plagioclase feldspar and garnet with subordinate amounts of titanite. White mica and biotite are oriented oblique to or along the dominant grain-shape fabric. Garnet porphyroblasts are partly replaced by biotite and/or clinozoisite.

Locality 5. (27H, 744555/152240). Metabasic rock in the marginal, structurally upper part of a dike-like body (c. 30–40 m thick) in the lower part of the Tsäkkok Lens. More central parts of the body (to the east) contain eclogite assemblages. The marginal metabasic rock is c. 5 m beneath the contact to host quartzo-feldspathic to more pelitic schist. It is coarse-grained and dominated by blue-green amphibole (M_3) and epidote/clinozoisite with subordinate amounts of chlorite and sphene situated around opaque mineral phases, plagioclase feldspar and biotite. Coarse grains of relic zoisite are partially replaced by chlorite and clinozoisite. Some amphibole grains reveal a tendancy towards a barroisitic composition in cores (relic late M_2); rims are hornblende in composition.

Locality 6. (27H, 744405/155630). Metabasic dike in contact with quartzite in the upper part of the Sarek Lens. The sample was collected c. 1 dm beneath the contact to the quartzite. It is foliated and contains blue-green amphibole displaying a hornblende composition and plagioclase feldspar with subordinate garnet and opaque minerals.