K/Ar ages from the Basal Gneiss Region, Stadlandet area, Western Norway

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K/Ar and $^{40}Ar/^{39}Ar$ geochronology of minerals from the Stadlandet region, Norway, is complicated by the presence of excess ^{40}Ar in many samples. There is a correlation between excess ^{40}Ar concentration and textural occurrence of samples. Amphiboles and micas closely associated with eclogite pods are likely to contain significant concentrations of excess ^{40}Ar while samples from the country rocks are not. K/Ar and $^{40}Ar/^{39}Ar$ ages for hornblende from the country rocks suggest that post-metamorphic cooling through 500°C occurred about 410 Ma ago, shortly after eclogite formation. Biotites containing no excess ^{40}Ar cooled through 300°C about 370 Ma ago. A post-metamorphic cooling rate of about 5°C/Ma can be inferred.

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Both the petrogenesis and age of the eclogite pods of the Basal Gneiss Region of Western Norway have been the subject of considerable debate. This study was initiated to date the formation of the eclogites by the K/Ar method. The primary mineralogy of the eclogites is anhydrous and contains no potassium-bearing phases (Lappin & Smith 1978). However, in many cases the eclogites are retrograded to hydrous, potassium-bearing assemblages. Several authors (Lappin & Smith 1978, McDougall & Green 1964) have suggested that these secondary assemblages formed at an early stage in the history of the eclogites. If this assumption is correct and if post-metamorphic cooling was rapid, K/Ar ages of the secondary potassium-bearing minerals should closely approximate the time of formation of eclogites.

Since this study commenced, three point garnet, pyroxene, and whole-rock Sm/Nd ages have been determined for three eclogite pods from the immediate study area (Griffin & Bruckner 1980, Mearns & Lappin 1982). These isochrons firmly establish the eclogite formation in the Stadlandet area as a Caledonian event (447 ± 20, 408 ± 8, 414 ± 31). With this knowledge it is apparent that many of the minerals dated by the K/Ar method have anomalously old apparent ages. This suggests that ^{40}Ar is present in excess of that produced in situ since eclogite formation. Excess ^{40}Ar is found in both amphiboles and micas. In addition to age information it is the purpose of this study to explain factors controlling the distribution of excess ^{40}Ar in the eclogites.

Geologic setting

The samples examined during this study were collected in the Stadlandet peninsula and the adjacent Flatraket area of Western Norway (Fig. 1). Though locally the rocks of the Basal Gneiss Region are at granulite grade, they are predominately at amphibolite grade in the study area (Lappin 1966). The dominant rock types in the study area are grey gneisses (plagioclase gneiss) and banded and augen gneisses (two feldspar gneiss). Garnet-mica schist, hornblende schist, garnet amphibolite, quartzite, pegmatite, and eclogite constitute about ten percent of the total and are described in detail by Lappin (1966).

It is generally believed that the Basal Gneiss Complex is the deepest exposed structural level of the Norwegian Caledonides (Cuthbert et al. 1983). Its structural and metamorphic history is complex in that it was affected by the Svecofennian, Sveconorwegian, and Caledonian orogenic events. A peculiar feature of the Basal Gneiss Complex is the common occurrence of lithologies which preserve relict high-pressure mineralogies, the best known being eclogites. Some eclogites occur in association with other ultramafic rock bodies, such as dunite, and commonly have the form of layers of lenses. Other eclogites occur as isolated lenses or boudinage layers within the country rock; this eclogite type is the subject of this paper.

Garnet and clinopyroxene are the dominant minerals in the eclogites but orthopyroxene, oli-

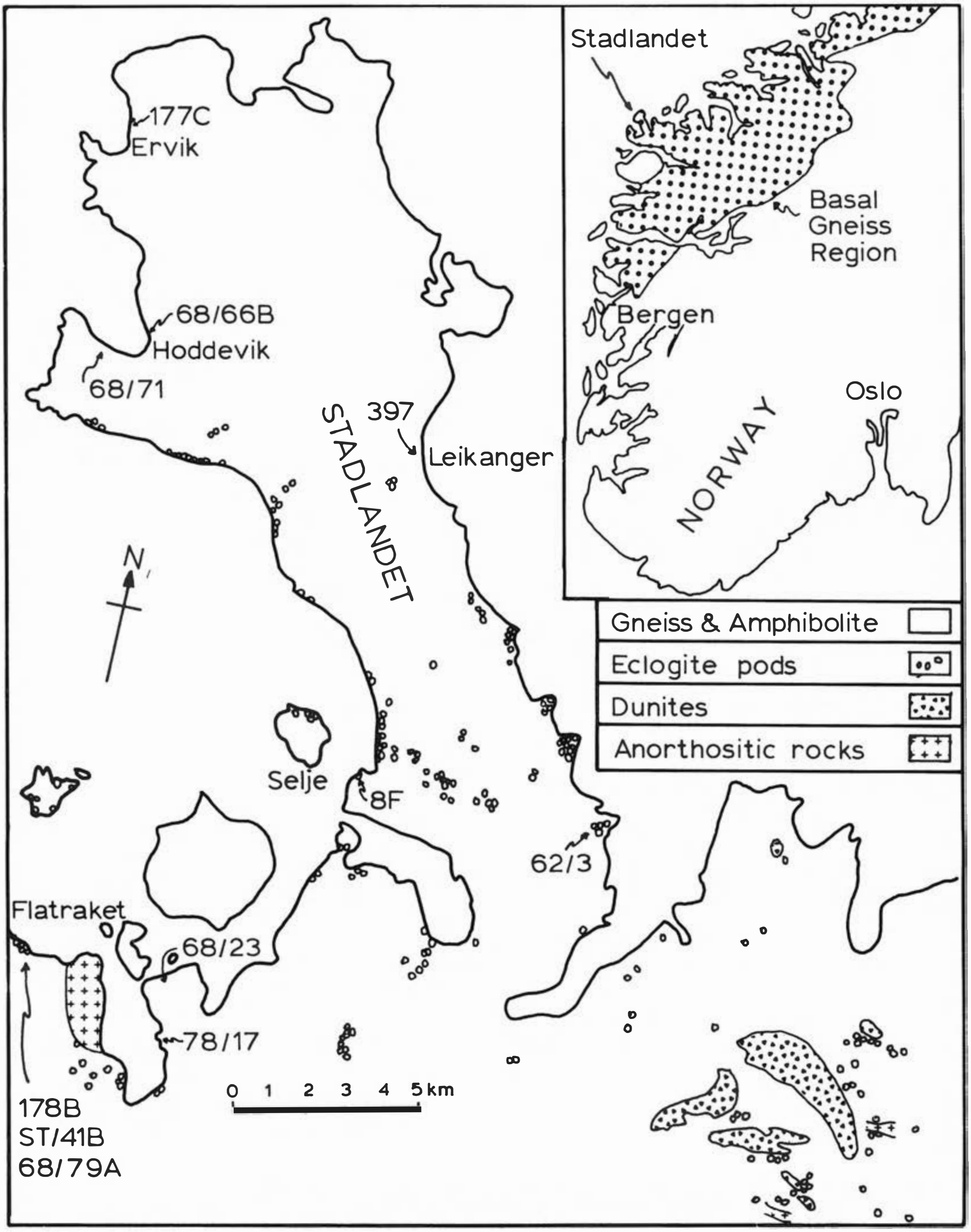

Fig. 1. Map of the Stadlandet region showing sample localities and the position of various ultramafic rock localities (after Lappin 1966).

vine, kyanite, quartz, rutile, apatite, and zircon may also occur as primary minerals (Lappin & Smith 1978). Most of the eclogite pods show some retrograde features. These can be grouped into three mineral assemblages, each with a distinct paragenesis and distinct mineral compositions (Lappin & Smith 1978). Early retrograde minerals are commonly amphiboles, micas, zoisite, tourmaline, sphene, and carbonates. Amphiboles from this group will be referred to as *early amphiboles*. In some instances the early minerals show stable mutual contacts with primary minerals. However, in other cases textural criteria indicate the secondary nature of the early minerals (Lappin & Smith 1978). Various geobarometers and geothermometers suggest that they formed at lower temperatures and pressures than the primary assemblages (Lappin & Smith 1978). Chemical uniformity of the early minerals, regardless of textural differences, suggests that all of the early minerals represent a retrograde adjustment after the initial formation of the eclogite pods (Lappin & Smith 1978). Continued retrograde adjustment is characterized by *symplectic amphibole* and plagioclase replacing both primary and early minerals. The chemical composition of these minerals indicates a distinct mineralogic group (Lappin & Smith 1978). Some eclogites are totally recrystallized to form amphibolite. Amphibolite formed from these *recrystallized amphiboles* usually occurs as rims which totally enclose the eclogite pods and can easily be observed in the field (Lappin 1966). The recrystallized amphibolite appears to be in equilibrium with minerals of the enclosing *country rock*. Addition of H_2O and K_2O is required to complete all of the three successive stages of retrograde alteration (Lappin & Smith 1978).

Previous isotopic dating

In recent years geochronology has contributed a great deal to the understanding of the timing of events in the Basal Gneiss Region. Different parts of the region apparently record Svecofennian (1950–1650 Ma), Sveconorwegian (900–1200 Ma), or Caledonian (350–650 Ma) events (Bruckner 1974; Lappin et al. 1979). Whole-rock Rb/Sr isochron ages from different parts of the Basal Gneiss Region give Svecofennian ages ranging from 1760 to 1682 Ma (Lappin et al. 1979; Pidgeon & Raheim 1972, Mysen & Heier 1972) and generally agree within the limits of analytical uncertainties. These ages have been interpreted as the age of formation of igneous precursors of the gneisses (Lappin et al. 1979). Most previously determined K/Ar, $^{40}Ar/^{39}Ar$, model Rb/Sr, and Rb/Sr mineral isochron ages fall within the range 372–495 Ma (McDougall & Green 1964, Bryhni et al. 1971, Lappin et al. 1979, Bruckner 1972, Pidgeon & Raheim 1972). This implies that these minerals formed or their isotopic systems were largely reset during the Caledonian Orogeny. Some K-Ar ages for micas, amphiboles, and pyroxene do, however, greatly exceed Caledonian ages (McDougall & Green 1964). Ages of 401 and 418 Ma have been determined for two U-poor zircon samples from eclogite pods by the $^{238}U/^{206}Pb$ method (Krogh et al. 1974), and were interpreted as crystallization ages. More recently, eight Sm/Nd isochrons using garnet, clinopyroxene, and whole-rock from eclogite pods indicate ages of 447 to 408 Ma (Griffin & Bruckner 1980, Mearns & Lappin 1982), and were also interpreted as crystallization ages. Other ages between these two extremes (Svecofennian and Caledonian) are observed less frequently for samples from the Basal Gneiss Complex (Lappin et al. 1979, Bruckner 1974).

Whole-rock dating by the Rb/Sr isochron method indicates an age of 1760 ± 70 Ma for gneisses of the Stadlandet Peninsula (Lappin et al. 1979). Discordant zircons from the same gneisses loosely constrain an upper concordia intercept of similar age and this is taken as confirming evidence of a Svecofennian age for formation of the gneisses (Lappin et al. 1979). Three eclogite pods from the immediate study area have been dated with the Sm/Nd method and gave similar ages, 447 ± 20, 408 ± 8, and 414 ± 31 Ma (Griffen et al. 1980, Mearns & Lappin 1982). K/Ar and Rb/Sr apparent ages for minerals from near the study area are largely Caledonian (Lappin et al. 1979, Bruckner 1972, McDougall & Green 1964, Bryhni et al. 1971). Some K/Ar age determinations for minerals from the area are anomalously high, and have been attributed to excess ^{40}Ar (McDougall & Green 1964). In most cases the excess ^{40}Ar has been associated with eclogite pods.

Results

K/Ar analytical data for 27 amphiboles and 10 biotites are presented (Tables 1 and 2, respec-

Table 1. Analytical data for K/Ar age determinations for amphiboles.

Sample Number	% K	$^{40}Ar_R$ *	$^{40}Ar_R$ %	Apparent Age × 10⁶ yrs.	Textural Occurr.
178B	1.572	2.629	96.2	386 ± 11	CR
		2.664	86.1	391 ± 12	
303A	0.532	0.917	67.9	396 ± 12	R
		0.918	82.2	397 ± 11	
68/66B	0.850	1.500	95.9	405 ± 12	CR
68/23	1.168	2.074	96.1	407 ± 12	CR
68/79B	0.620	1.107	82.1	409 ± 12	S
78/17	1.148	2.072	97.6	413 ± 12	CR
395B	0.648	1.209	87.6	426 ± 12	CR
		1.221	88.5	429 ± 12	
177C	0.432	0.819	93.8	432 ± 13	CR
68/71	0.918	1.768	97.7	438 ± 12	CR
127H	0.377	0.741	59.2	446 ± 14	R
397	1.493	3.229	97.6	485 ± 14	CR
127H/A	0.389	0.839	64.5	483 ± 15	R
		0.851	78.7	490 ± 14	
68/79A	0.299	0.983	88.4	694 ± 20	S
		0.992	79.7	699 ± 20	
ST/41A	0.401	1.426	77.3	740 ± 22	S
		1.389	87.6	724 ± 21	
62/3	0.329	1.322	85.6	817 ± 24	E
		1.305	92.4	809 ± 23	
ST/41B	0.373	1.506	82.7	820 ± 24	S
226E	0.251	1.239	81.6	961 ± 27	S
68/53A	0.274	1.810	67.1	1197 ± 37	E
		1.752	91.7	1169 ± 34	
68/53B	0.237	1.772	83.2	1309 ± 37	E
226B	0.197	1.774	85.1	1490 ± 42	E
68/78A	0.181	2.169	96.0	1797 ± 52	E
208A	0.136	1.631	75.6	1807 ± 52	E
304B	0.146	1.869	95.5	1873 ± 53	E
62/37	0.222	4.148	89.5	2343 ± 67	E
68/84	0.067	2.710	89.0	3449 ± 99	E
		2.537	89.2	3348 ± 96	E
ST/43A	0.033	1.729	86.2	3856 ± 114	E
ST/43B	0.028	3.32F	71.7	5208 ± 150	E

Decay constants are those recommended by Steiger and Jager (1977).

CR – country rock, R – recrystallized, S – symplectic, E – early amphibole

* STPCM³ × 10^{-5}/g

Table 2. Analytical data for K/Ar age determinations for biotites. Decay constants are those recommended by Steiger and Jager (1977).

Sample Number	% K	$^{40}Ar_R$ *	% $^{40}Ar_R$	Apparent Age × 10⁶ yrs.	Textural Occurr.
68/66B	6.099	9.006	60.9	344.7 ± 8.5	A
		8.733	98.1	335.2 ± 6.7	
177C	7.469	11.892	98.7	369.1 ± 7.3	G
78/17	7.096	11.312	98.6	369.5 ± 7.4	A
68/71	7.836	12.592	98.6	372.2 ± 7.4	A
68/23	7.764	12.987	98.7	385.9 ± 7.7	A
395	7.832	14.503	97.4	422.7 ± 8.4	G
178B	7.817	15.068	98.0	438.0 ± 8.7	A
		15.067	89.2	438.0 ± 9.0	
397	7.485	15.835	97.7	475.6 ± 9.5	G
8F	7.903	33.373	95.0	850.2 ± 17.1	E
8F	7.492	31.222	96.0	841.3 ± 16.9	E
62/3	7.076	55.332	98.3	1351.2 ± 26.7	E
		55.879	95.5	1360.6 ± 27.4	

A – amphibolite, G – gneiss, E – eclogite
Error estimates are 2σ. *STPcc × 10^{-5}/g

tively). Two preliminary $^{40}Ar/^{39}Ar$ incremental release age spectrum determinations are also presented (Table 3). These data are also displayed graphically on release spectrum diagrams (Figs. 2 and 3). In determining analytical uncertainties the uncertainty in the J-value is important. However, in comparing successive increments in an individual sample there is no need to consider the possible error in J since the entire sample experienced the same neutron flux during irradiation. To test for plateau behavior in each sample, only analytical uncertainties were considered at two standard deviations. All biotites except sample 8F have a corresponding hornblende from the same sample.

Biotites show a wide range of apparent ages, 340 to 1356 Ma (Table 2). Samples with apparent ages in excess of 400 Ma are considered to be anomalous, as is the sample with an apparent age less than 360 Ma. A major factor in this line of reasoning is that these biotites have all been dated using the Rb-Sr method (Mearns, pers. comm.) and range in age from 357 to 381 Ma with an average 373 Ma. Only four of the ten biotites have K/Ar ages which are in this range. Since biotite is known to have about the same blocking temperature for both the K/Ar and Rb/Sr systems (Jager 1979), better agreement between the two sets of isotopic ages was expected. As will be discussed later, those biotites with anomalously old K/Ar ages are thought to contain ^{40}Ar in excess of that produced in situ by radioactive decay of ^{40}K. The relatively young apparent age for biotite 68/66B, 340 Ma, is also considered to be anomalous and is somewhat more disturbing. It could be caused by a variety of factors including inhomogeneous ^{40}Ar and K in the two splits used for analysis, or a systematic error in laboratory procedures. Both Ar and K concentration were measured in duplicate (Table 2) and reproduced reasonably well, suggesting that inhomogenous K and Ar distributions are

Table 3. $^{40}Ar/^{39}Ar$ analytical data for both samples. Increments 5, 6 and 7 contribute to the plateau age for 78/17 hornblende. All increments excluding the first contribute to the plateau age for 68/66B biotite.

Temp °C	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{39}Ar_K$ (% of total)	$^{40}Ar_R$ (%)	$^{39}Ar_K$ (× 10–12 moles)	Apparent K/Ca	Apparent Age (Ma)
Sample 78/17 Hornblende (K-Ar age = 413 + 8 Ma) J = 0.008600								
600	53.056	0.726	0.06991	1.1	61.2	0.116	0.715	444.0 ± 19.9
850	44.380	0.312	0.04553	4.8	69.7	0.521	1.66	425.7 ± 4.5
925	34.923	2.646	0.01954	3.3	84.0	0.354	0.196	406.0 ± 4.5
975	32.403	3.323	0.01251	7.1	89.4	0.763	0.156	401.2 ± 4.0
1025	30.518	3.736	0.00391	26.4	97.1	2.84	0.139	409.7 ± 4.0
1050	30.514	3.738	0.00388	20.3	97.2	2.18	0.139	409.8 ± 4.0
1075	30.595	3.705	0.00392	15.1	97.1	1.63	0.140	410.6 ± 4.0
Fuse	32.195	3.660	0.00252	41.8	98.6	2.35	0.142	435.2 ± 4.2
						Total gas		415.9
						Plateau age		409.9 ± 0.5
Sample 68/66B Biotte (K-Ar age – 340 ± 8 Ma) J = 0.006030								
600	28.070		0.03872	2.33	59.22	0.475		172.3 ± 14.0
650	38.428		0.00182	41.07	98.58	8.383		371.2 ± 4.1
750	41.177		0.00887	8.40	93.62	1.715		377.0 ± 5.2
850	42.054		0.01119	12.21	92.12	2.495		378.7 ± 4.6
950	43.401		0.01658	13.53	88.70	2.761		376.6 ± 4.8
1025	42.839		0.01444	17.37	90.02	3.545		377.2 ± 4.5
Fuse	86.263		0.16227	5.09	44.41	1.039		374.9 ± 11.2
						Total gas		370.2
						Plateau age		374.6 ± 2.9

not the problem. Biotite 68/66B was dated by the $^{40}Ar/^{39}Ar$ method. Almost 98 % of the total gas released from the sample agrees within analytical uncertainties yielding a plateau age of 375 ± 6 Ma (Figure 2). The total gas age is slightly lower, 370 Ma, perhaps representing a small amount of ^{40}Ar loss. These results are very different from the K/Ar age but are in excellent agreement with the Rb/Sr ages. The release spectrum shows a distribution of Ar consistent with closed system behavior. The $^{40}Ar/^{39}Ar$ method used only one split of the sample, and thus possible errors related to sample inhomogeneity are eliminated (Dalrymple & Lanphere 1971). Sample inhomogeneity or a systematic analytical error could account for the anomalously low K/Ar ages, but neither can be singled out as the certain cause. The plateau age, 375 Ma, is taken to be the best estimate of the age of sample 68/66B. Accepting the $^{40}Ar/^{39}Ar$ age for sample 68/66B, 5 of the 8 K/Ar ages for biotites from the country rock average 374 ± 14 Ma. The agreement of a majority of the K/Ar ages with the Rb/Sr ages is excellent. The remaining three biotites from the country rocks (397, 178B, 395B) all have Caledonian ages but significantly exceed the best estimates for post-metamorphic cooling through 300°C. Small amounts of excess ^{40}Ar incorporated into these biotites could explain this discrepancy.

The formation of the remaining two biotites (8F and 62/3) from eclogite pods is interpreted to be a retrograde alteration of primary eclogite minerals. A chemical analysis of mica with a similar textural occurrence from another eclogite pod shows it to be phlogopite rather than biotite. These two samples may also be phlogopitic in composition. Both of these micas have K/Ar apparent ages which greatly exceed that of other biotites in the area (Table 2). It is suggested that these anomalously high apparent ages are also the product of excess ^{40}Ar.

Amphiboles show by far the widest range of K/Ar apparent ages, 389 to 5208 Ma (Table 1). Obviously some of the ages are anomalous. The data for the amphiboles can conveniently be treated in terms of four groups which correspond to their petrographic occurrence as defined by Lappin & Smith (1978). These include: 1) *country rock amphiboles*, 2) *recrystallized*, 3) *symplectic* and 4) *early amphiboles* from the eclogite pods.

The apparent ages of amphiboles from the

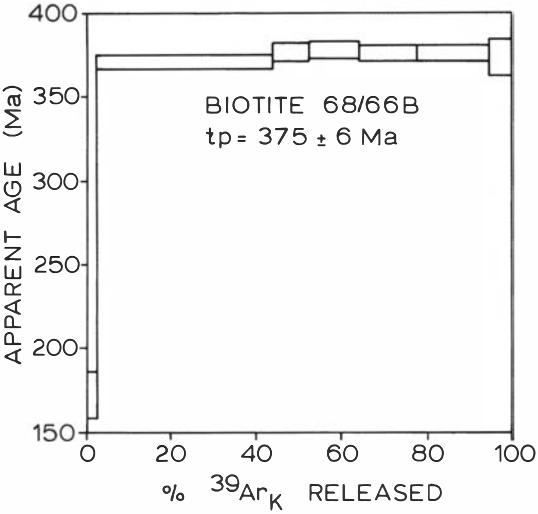

Fig. 2. Incremental release age spectrum diagram for biotite 68/66B. A large majority of the sample contributes to the age plateau (tp) equal to 375 ± 6 Ma.

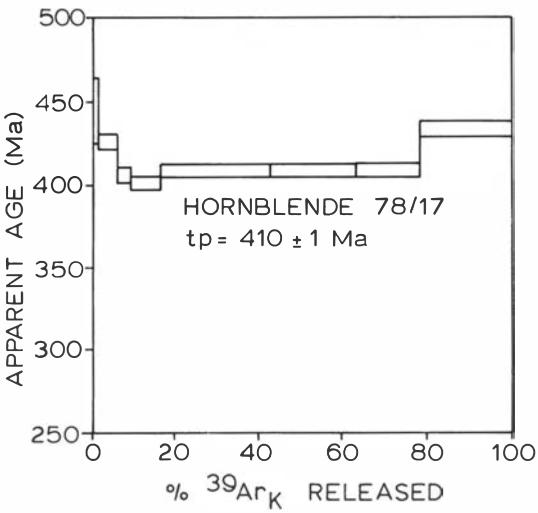

Fig. 3. Incremental release age spectrum diagram for hornblende 78/17. Three middle increments have virtually identical age and define an age plateau (tp) equal to 410 ± 01 Ma, interpreted to be the undisturbed portion of the sample. The saddle-shaped spectrum indicates the presence of excess ^{40}Ar.

country rocks, 389 to 485 Ma, are all within the range of Caledonian ages. These samples have a higher K concentration than any of the other amphiboles (Table 1). Five of the eight country rock amphiboles plus one recrystallized and one symplectic amphibole agree within two standard deviations of the mean, 407 ± 25 Ma. These seven samples form the largest cluster of K/Ar apparent ages for the hornblende samples.

A single hornblende was analyzed by the $^{40}Ar/^{39}Ar$ method. The results are presented as a incremental release age spectrum diagram (Fig. 3). A majority of the sample gas yields a plateau age of 410 ± 1 Ma, in good agreement with the K/Ar age of 413 ± 12 Ma. The plateau age represents that part of the hornblende sample in which the K/Ar system is least disturbed, and is the best estimate of the time of closure to ^{40}Ar loss. The similarity of this age to the total gas age, 416 Ma, demonstrates that the disturbance in the system is minimal. The initial and late increments both have apparent ages which exceed the plateau age. This saddle-shaped type spectrum is believed by Lanphere & Dalrymple (1976) to be indicative of excess ^{40}Ar.

The recrystallized amphiboles all have Caledonian K/Ar apparent ages 397 to 487 Ma (Table 1).

The range in apparent ages for symplectic amphiboles is 409 to 962 Ma (Table 1). Only the youngest of these five samples has a Caledonian age. Because Sm-Nd ages indicate that eclogites formed during the Caledonian Orogeny (Griffin & Bruckner 1980, Mearns & Lappin 1982), and because these amphiboles represent a retrograde alteration of the eclogites, the K/Ar ages for the remaining four symplectic amphiboles must be considered suspect.

The early amphiboles range in apparent age from 1183 to 5208 Ma (Table 1). All ages are older than Caledonian and, following the same arguments presented above, these apparent ages should be considered anomalous.

In addition to these observations, there appears to be a correlation between the K concentration of the amphiboles and several other features of the rocks. Petrographic occurrence correlates with the K concentration of the amphiboles. The order of increasing K concentration of the amphiboles is as follows: *early < symplectic < recrystallized < country rock*. This is consistent with the observations of Lappin & Smith (1978) which suggest that K must be added to the primary eclogite assemblages in order to complete the retrograde reactions.

Samples with higher K concentrations tend to have lower apparent ages (Fig. 4). Those samples with K concentrations of 0.4% or greater have Caledonian apparent ages and are largely country rock and recrystallized amphiboles. If

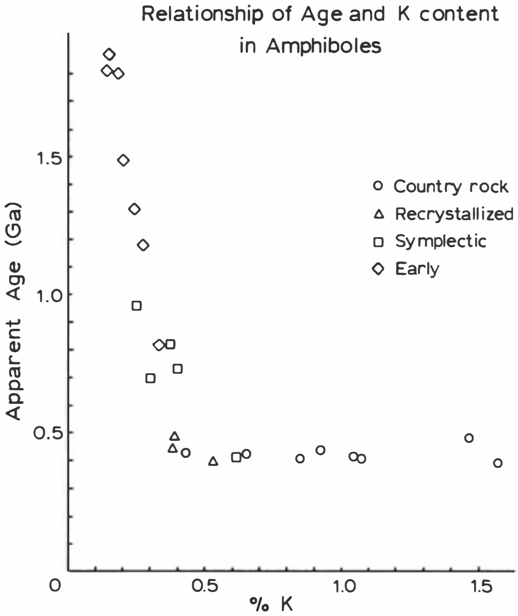

Fig. 4. Diagram showing the relationship of apparent age and potassium content in amphiboles. Note that amphiboles with greater than 0.4 weight percent K are mostly country rock and recrystallized amphiboles and have more or less uniform ages. Amphiboles with less than 0.4 weight percent K are symplectic and early amphiboles which have much older apparent ages, indicative of excess ^{40}Ar.

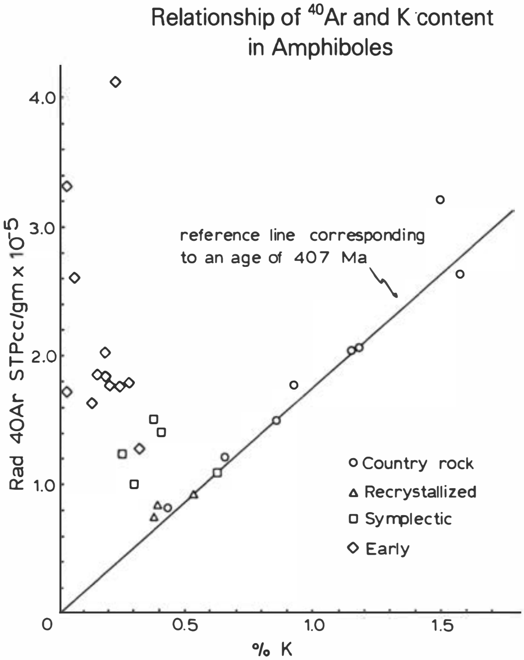

Fig. 5. The plot of K and Ar concentrations is somewhat analagous to isochron plots. Those samples on the reference line have ages equivalent to 407 Ma, those above the line have ages in excess of 407 Ma and below the line less than 407 Ma. Note that samples on or near the line are country rock and recrystallized amphiboles and those which are most distant from the line are early and symplectic amphiboles.

excess ^{40}Ar is the cause of the high apparent ages, this correlation might be expected, since the apparent ages of those samples with low K concentrations would most readily show the effects of excess ^{40}Ar.

The relationship between excess ^{40}Ar and K concentration is also illustrated in Fig. 5. This plot is analogous to isochron diagrams and samples of the same age that contain no initial ^{40}Ar should fall on a line passing through the origin, the slope of which is proportional to the age. The reference line on Fig. 5 has a slope equivalent to an age of 407 Ma. Samples plotting below the line are younger, above the line older. It is particularly evident that samples from different groups have different K/Ar systematics. Country rock and recrystallized amphiboles plot on or near the reference line, but the range in K concentration of the recrystallized amphiboles is much smaller. With one exception the symplectic amphiboles are significantly displaced away from the line in the direction of excess ^{40}Ar. Early amphiboles show a similar though larger displacement. The latter two form coherent groups in which samples do not conform with the fundamental requirements for dating.

Discussion

Numerous lines of evidence suggest the presence of excess ^{40}Ar in some samples. In several instances K/Ar ages exceed the Rb/Sr ages of biotites. Both are known to have a blocking temperature of about 300°C (Jager 1979, Harrison et al. 1984) and therefore should record a similar age. The older K/Ar ages suggest excess ^{40}Ar.

It is well established that hornblende has a distinctly higher blocking temperature than does biotite (Harrison 1981, Harrison et al. 1984). Therefore, if cooling of a rock were sufficiently slow to produce a discordance in K/Ar ages for coexisting hornblende and biotite, hornblende should have an older apparent age. In a number

Table 4. The concentration of excess ^{40}Ar is presented assuming a 'true' age of 410 Ma for cooling through the hornblende blocking temperature. $^{40}Ar_R$ is determined by the K concentration and an age of 410 Ma.

Sample Number	$^{40}Ar_m$ ++	Apparent Age	$^{40}Ar_R$ **	$^{40}Ar_{Excess}$ ++	Textural Occurence
68/71	1.768	437.7	1.642	0.126	CR
127H	0.741	445.6	0.674	0.070	R
397	3.229	484.9	2.670	0.559	CR
127H/A	0.845	486.5	0.696	0.149	R
68/79A	0.988	696.6	0.535	0.453	S
ST/41A	1.408	732.0	0.717	0.691	S
62/3	1.314	813.0	0.588	0.726	E
ST/41B	1.506	820.1	0.667	0.839	S
226E	1.239	961.5	0.449	0.790	S
68/53A	1.781	1183.4	0.490	1.291	E
68/53B	1.772	1308.8	0.424	1.348	E
226D	1.774	1489.7	0.352	1.422	E
68/78A	2.169	1797.4	0.324	1.845	E
208A	1.631	1806.8	0.241	1.390	E
304B	1.869	1873.4	0.261	1.608	E
62/37	4.148	2342.6	0.397	3.751	E
68/84	2.710	3449.3	0.120	2.590	E
	2.510	3348.4	0.120	2.417	
ST/43A	1.729	3854.8	0.059	1.670	E
ST/43B	3.320	5208.2	0.050	3.270	E

++ – $\times 10^{-5}$ STPCM^{3}g^{-1}
** – $\times 10^{-5}$ STROM^{3}g^{-1} assuming 410 Ma as 'true' age

of samples this relationship is reversed, suggesting some biotite samples contain excess ^{40}Ar.

Some early and symplectic amphiboles have anomalously high K/Ar ages in that they exceed the Sm/Nd age of the eclogites in which they occur, the Rb/Sr age of the country rock gneisses, and in one instance the age of the earth. An obvious interpretation is that these amphiboles also contain excess ^{40}Ar.

Finally excess ^{40}Ar is indicated by the incremental heating of hornblende 78/17. Lanphere & Dalrymple (1976) observed saddle-shaped age spectra, similar to the age spectrum of 78/17, in samples known to contain excess ^{40}Ar. Harrison & McDougall (1981) predicted that excess ^{40}Ar should be concentrated near grain boundaries in samples provided that it did not equilibrate throughout the crystals during the event that introduced excess ^{40}Ar into the samples. This would be observed as high apparent ages for initial low temperature increments. Since that time many samples have been analyzed in which apparent age gradients, resulting from excess ^{40}Ar concentration gradients, have been observed in low temperature increments.

A likely source of the excess ^{40}Ar is the country rocks of the area. These rocks formed about 1700 Ma ago and may have been disturbed during the Sveconorwegian event. In either case a sufficiently long period of time passed for relatively large concentrations of ^{40}Ar to accumulate in K-bearing minerals of the region prior to the Caledonian metamorphism. As these rocks were heated during the Caledonian event, ^{40}Ar would have been released from minerals as prograde metamorphism raised the ambient temperature over the blocking temperature of the various minerals present. Estimates of the P-T conditions of Caledonian metamorphism indicate that any common K-bearing mineral would have completely degassed. If the escape of Ar from the terrane was impeded, a significant partial pressure of Ar would have developed during metamorphism. Numerous studies have demonstrated that minerals which crystallize in an environment with a significant Ar partial pressure often contain excess ^{40}Ar (Pankhurst et al. 1973, Giletti 1971, Foland 1979, Seidemann 1976). One possible explanation for the presence of excess ^{40}Ar is that it diffused into newly formed minerals after they crystallized, because of the concentration difference between the crystals and the pore fluid which contained Ar. The $^{40}Ar/^{39}Ar$ incremental release analysis of hornblende sample 78/17 supports the suggestion that excess ^{40}Ar diffused into that sample.

Figs. 4 and 5 suggest that early and symplectic amphiboles contain more excess ^{40}Ar than do other amphiboles from the area. An alternative explanation would be that all might have similar excess ^{40}Ar concentrations and that the early amphiboles have highest apparent ages because they have the lowest K concentrations. Country rock amphiboles from throughout the region, especially the incremental heating of 78/17, illustrate that cooling through 500°C last occurred about 410 Ma ago. Using this as the 'true' age for the hornblende, the amount of ^{40}Ar required by its ^{40}K concentration to produce an age of 410 Ma can be calculated (Table 4). It is clear that the amphiboles in eclogite pods contain more excess ^{40}Ar than do the country rock and recrystallized amphiboles. Symplectic amphiboles contain an intermediate amount. Micas in the eclogite pods also contain higher concentrations of excess ^{40}Ar than do micas from the country rocks.

As discussed above, each successive retrograde mineral assemblage represents an incomplete chemical adjustment to the final equilibrium conditions. The recrystallized eclogites (now amphibolites) and country rocks are taken to represent the final equilibrium conditions during the Caledonian event. The incomplete conversion to chemical equilibrium preserved in the retrograde assemblages is mirrored by the excess Ar concentrations. The samples which appear to record the final P-T conditions of the Caledonian metamorphism are those which contain little or no excess ^{40}Ar, indicating degassing of ^{40}Ar from the metamorphic terrane and the complete resetting of K/Ar mineral ages. There is a positive correlation in the degree that these two features approach equilibrium, suggesting that perhaps both features have a similar cause. It is generally accepted that retrograde reactions are facilitated by the presence of an aqueous phase. In the absence of an aqueous phase, solid state diffusion often proceeds too slowly to allow complete chemical adjustment, thus allowing a metastable mineralogy to persist. In the case of these eclogite pods, mass balance considerations require the addition of H_2O to complete each of the successive retrograde reactions outlined above (Lappin 1979). Where H_2O was available, recrystallization occurred, the samples reached chemical equilibrium, and nearly all initial ^{40}Ar was lost from the system. Where the retrograde reactions were incomplete, probably due to insufficient H_2O to allow equilibration, initial ^{40}Ar remained in the system and was incorporated as excess ^{40}Ar in minerals of those assemblages. The extensive recrystallization of eclogite to amphibolite along rims may have helped to prevent complete equilibration during the last stage of metamorphism. Foland (1979) inferred that the absence of a hydrous fluid phase may have greatly restricted the mobility of argon in the Wilmington complex during Acadian metamorphism. Data presented here support the concept that the mobility of argon is greatly reduced in the absence of a hydrous fluid phase.

Summary

K/Ar and ^{40}Ar/^{39}Ar isotopic dating presented here suggests that rocks in the Stadlandet area cooled through the blocking temperature of hornblende (500°C) about 410 Ma ago, following high grade Caledonian metamorphism. K/Ar, ^{40}Ar/^{39}Ar and Rb/Sr dating of biotite from this terrane demonstrates that post-metamorphic cooling through 300°C occurred about 370 Ma ago. A linear cooling rate of 5°C/Ma is inferred. Cooling rates of this magnitude are common in high-grade metamorphic terranes.

Numerous micas and amphiboles have K/Ar apparent ages which exceed these best estimates for closure times. This anomalous behavior is attributed to the presence of excess ^{40}Ar. The basement gneisses are known to be about 1700 Ma old and are considered to be the likely source of excess ^{40}Ar.

Country rock minerals contain little excess ^{40}Ar and best record the time of closure of the K/Ar system. The K/Ar system is generally disturbed in minerals of the eclogite pods and these minerals are therefore not suitable for age determination by K/Ar methods. Early alteration minerals contain the highest amount of excess ^{40}Ar with lesser amounts present in symplectic minerals and eclogites which are recrystallized to form amphibolites. The amount of contamination with excess ^{40}Ar correlates with the degree to which the original eclogites mineralogy adjusted to the final P-T conditions of the Caledonian metamorphism. The incomplete retrograde adjustment of the eclogites is attributed to insufficient H_2O to allow recrystallization. Similarly, the mobility of Ar may be inhibited by the absence of a hydrous fluid phase.

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Analytical Methods. – Standard mineral separation techniques were used in order to produce samples with a purity of 99 % or greater. A Corning-EEL (model 450) flame photometer was used for duplicate potassium measurements. Argon was extracted from the samples using radiofrequency induction heating, and standard purification methods were used to isolate the rare gasses. The extraction system is on-line to an AEI-MSIO mass spectrometer. The concentration of ^{40}Ar was determinea by isotope dilution.

Samples analyzed by the ^{40}Ar/^{39}Ar incremental heating method were irradiated at the U. S. Geological Survey TRIGA reactor in Denver, Colorado following established procedures (Dalrymple et al. 1981). MMhb-I (Alexander et al. 1978) was used as the irradiation flux monitor. These samples were also heated by radiofrequency induction and were purified by standard techniques. A fully automated V. G. Isotopes (Micromass 1200) mass spectrometer was used for data collection.

Decay constants used in the age calculations were those recommended by Steiger & Jager (1977) and all analytical uncertainty estimates are two sigma.

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