Proterozoic thermal activity in the Archaean basement of the Disko Bugt region and eastern Nuussuaq, West Greenland: evidence from K-Ar and ^{40}Ar-^{39}Ar mineral age investigations

Henrik Rasmussen and Paul Martin Holm

K-Ar and ^{40}Ar-^{39}Ar analyses of amphiboles from Archaean amphibolites and gneisses show that Proterozoic tectono-thermal activity has played an important role in the metamorphic and structural development of the Precambrian rocks around north-eastern Disko Bugt and in eastern Nuussuaq. Proterozoic thermal activity lead to resetting of the K-Ar ages of amphiboles in eastern Nuussuaq, resulting in ages of *c.* 1750 to 1925 Ma; in the Disko Bugt area the effects are seen in total or partial resetting with K-Ar ages scattering mostly between 2750 and 1870 Ma. Resetting is caused either by total diffusion of earlier accumulated radiogenic argon or by complete recrystallisation of the amphiboles. Archaean ^{40}Ar-^{39}Ar ages obtained from mafic xenoliths within the Atâ tonalite show that not all parts of the area suffered argon loss during Proterozoic reheating. Incorporation of significant proportions of excess argon in some amphiboles is seen from ^{40}Ar-^{39}Ar mineral age spectra obtained for samples from supracrustal rocks and from mafic xenoliths in the Atâ tonalite.

Phlogopite phenocrysts from a lamproite stock yielded a K-Ar age of 1764 ± 24 Ma, identical to a previously determined K-Ar age of the matrix phlogopite. These ages probably date the emplacement of the lamproite, and mark the time after which no tectono-thermal events affected the area.

H.R.* & P.M.H., *Geological Institute, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.* *Present address: *Mærsk Olie og Gas AS, Esplanaden 50, DK-1263 Copenhagen K, Denmark.* E-mail: *h_rasmussen@vip.cybercity.dk.*

Keywords: ^{40}Ar-^{39}Ar ages, Archaean rocks, Disko Bugt, K-Ar ages, lamproite, Proterozoic metamorphism, West Greenland

Major parts of West Greenland are underlain by Archaean basement rocks; large parts of this basement have been reworked by later Proterozoic tectono-thermal events (Kalsbeek 1981). K-Ar age determinations on biotite from the gneisses near Jakobshavn/Ilulissat and from a gneiss near Qeqertaq, north-east Disko Bugt (Fig. 1), yielded early Proterozoic dates of *c.* 1.7 Ga (Larsen & Møller 1968), and were interpreted as the time at which the biotites had been reset or were recrystallised. Moreover, Pb-Pb whole-rock isochron dates of *c.* 1.85 Ga on marbles from the Rinkian and Nagssugtoqidian orogens of West Greenland, respectively to the north and south of the present area, give evidence of high-grade metamorphism at that time (Taylor & Kalsbeek 1990). Isotope data for the *c.* 2.8 Ga old Atâ tonalite, together with field evidence, suggested, however, that parts of the north-eastern Disko Bugt area had escaped Proterozoic deformation and metamorphism (Kalsbeek *et al.* 1988).

The objective of the present study is, by means of K-Ar and ^{40}Ar-^{39}Ar isotope analysis, to date amphiboles and phlogopites from gneisses, amphibolites and lamproites from the Disko Bugt region in order to outline areas affected by Proterozoic reheating and to find the extent of the area not significantly affected by these later events. A survey of the regional geology of the region is given by Garde & Steenfelt (1999) in this volume.

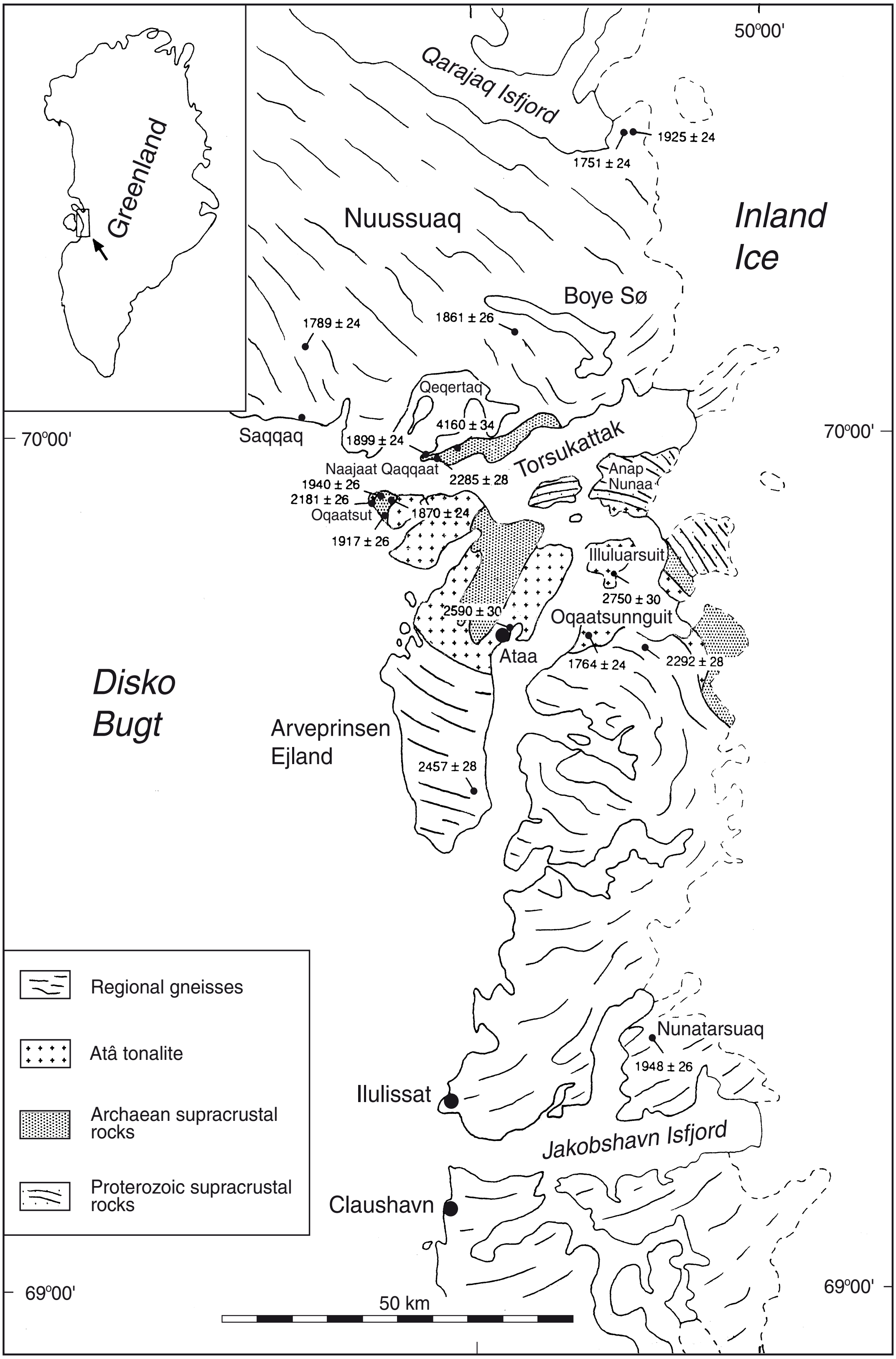

Fig. 1. Map of north-eastern Disko Bugt and eastern Nuussuaq showing the locations of samples collected for the K-Ar and ^{40}Ar-^{39}Ar investigations. Ages in Ma with 2σ errors. Geological units sketched from Garde & Steenfelt (1999, this volume).

Table 1. K-Ar isotope data for amphiboles from north-east Disko Bugt and eastern Nuussuaq

GGU no	mineral†	grain size (µm)	K(%)	$^{40}Ar^*$ ($10^{-5}cm^3/g$)	$\%^{40}Ar^*$	Age‡ (Ma)
Nuusuaq						
269780	ol-gr hbl	75-175	0.180±0.002	2.393, 2.428	96.25, 96.65	1925±24
269782	ol-gr hbl	75-175	0.574±0.004	6.592	96.14	1751±24
266843	bl-gr hbl	75-175	0.800±0.006	9.504, 9.511	99.23, 99.42	1789±24
272696	ol-gr hbl	75-175	0.408±0.002	5.305, 5.034	95.33, 98.30	1861±26
Najaat Qaqqaat and Oqaatsut						
349014	ol-gr hbl	75-175	0.665±0.012	8.607, 8.640	98.60, 98.74	1899±24
349053	pale ol-gr hbl	75-175	0.415±0.003	26.93, 25.65	99.10, 99.15	4160±34
349005	ol-gr hbl	75-175	0.212±0.004	3.861, 3.729	96.62, 98.00	2285±28
354319	bl-gr hbl	75-175	0.562±0.019	7.690, 7.529	98.43, 98.90	1940±26
354346	bl-gr hbl	75-175	0.589±0.004	9.936, 9.473	99.08, 98.18	2181±26
349023	pale bl-gr hbl	75-175	0.272±0.004	3.750, 3.468	96.35, 97.32	1917±26
354328	pale bl-gr hbl	75-175	0.288±0.008	3.655, 3.699	95.12, 97.63	1870±24
Ataa region						
272611	br-gr hbl	75-175	0.875±0.006	17.86, 17.76	99.32, 99.14	2457±28
352239	ol-gr hbl	75-200	0.805±0.003	14.39, 14.55	99.29, 99.21	2292±28
359139	pale ol-gr hbl	75-175	0.404±0.008	9.100, 9.025	97.96, 98.04	2590±30
352234	bl-gr hbl	75-150	0.662±0.002	16.03, 16.66	99.47, 99.51	2750±30
				17.16, 16.90	99.28, 99.24	
343955	phl	250-750	8.513±0.024	98.36, 99.58	99.48, 99.65	1764±24
Eastern Disko Bugt						
355612	pale gr hbl	75-175	0.192±0.004	2.694, 2.534	96.51, 96.95	1948+26

†: ol-gr hbl = olive-green hornblende; bl-gr hbl = blue-green hornblende; br-gr hbl = brown-green hornblende; phl = phlogopite.

‡: Ages are means calculated from different analyses; errors at 2σ.

$^{40}Ar^*$ = radiogenic Ar; the amount of $^{40}Ar^*$ recalculated to standard temperature and pressure.

$\%^{40}Ar^*$ is the percentage of total ^{40}Ar in the sample that is radiogenic.

Analytical techniques

High purity mineral separates of amphiboles were obtained from amphibolites, metagabbros and gneisses. Different sieve fractions used for analysis ranged in size between 75 and 175 µm. Phlogopite from an ellipsoidal nodule found in a lamproite stock at Oqaatsunnguit was taken directly from the nodule by hand. K was analysed by flame photometry on a Perkin Elmer® 5100 Atomic Absorption Spectrometer. K concentrations were checked against the international standard BB-24. Argon analysis for K-Ar and ^{40}Ar-^{39}Ar age determinations was carried out on an on-line AEI MS10C mass spectrometer fitted with a small 1.8 kG permanent magnet at the Danish Centre for Isotope Geology, University of Copenhagen. During the period of analysis, 13 runs on standard biotite LP-6 and 11 runs on standard muscovite P-207 resulted in mean values (in units of 10^{-5} cm^3 g^{-1} at standard T and P) of 4.323 ± 0.066 (1.5% rel.) and 2.830 ± 0.037 (1.3% rel.) for radiogenic ^{40}Ar respectively. Temperature values for the individual steps were not measured. Ages were calculated using the decay constants recommended by the IUGS subcommision on geochronology ($\lambda^{40}K$ = 5.543×10^{-10} a^{-1}; Steiger & Jäger 1977). Analytical techniques and methods are described in detail in Rasmussen (1992) and Holm (1991).

Results of K-Ar and ^{40}Ar-^{39}Ar age determinations

The spatial distribution of the K-Ar amphibole ages from this study is shown in Fig. 1 and the results are listed in Table 1. All uncertainties presented are 2σ errors.

Eastern Nuussuaq

Four K-Ar amphibole ages were obtained from the eastern part of Nuussuaq. In north-eastern Nuussuaq olive-green hornblende from a medium-grained amphibolitic inclusion (GGU 269780) in the gneisses yielded a date of 1925 ± 24 Ma. The amphiboles in this sample are anhedral and contain numerous micro-cracks.

Fresh and almost inclusion-free olive-green hornblende separated from the adjacent gneisses (GGU

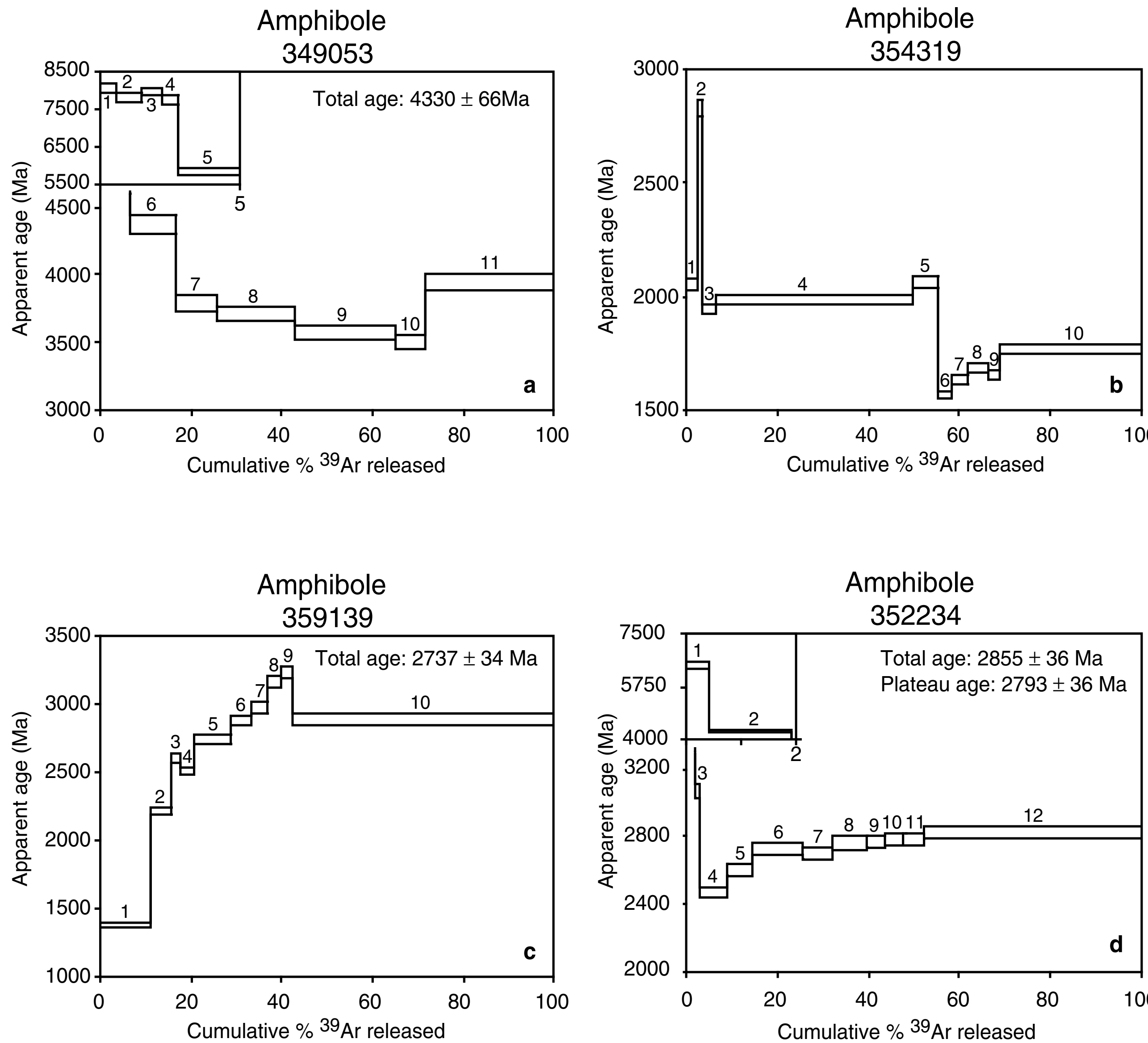

Fig. 2. ^{40}Ar-^{39}Ar age spectrum for hornblende: **a**: GGU 349053, Naajaat Qaqqaat. **b**: GGU 354319, Oqaatsut. **c**: GGU 359139, Ataa area. **d**: GGU 352234, Illuluarsuit Nunataat. Vertical width of the boxes represent 2σ errors.

269782) in this area gave a considerably younger date of 1751 ± 24 Ma.

From the central part of eastern Nuussuaq, about 7 km south of Boye Sø, olive-green hornblende separated from a medium-grained, almost undeformed diorite (GGU 272696) yielded a date of 1861 ± 26 Ma. The hornblende is fairly fresh but contains numerous parallel aligned opaque inclusions.

Further west, in the Sarqaq supracrustal rocks (Garde & Steenfelt 1999, this volume) a blue-green hornblende, obtained from a fine- to medium-grained amphibolite (GGU 266843), yielded a date of 1789 ± 24 Ma.

Comparison of these dates with existing chronological information is not straightforward. Larsen & Møller (1968) reported a K-Ar biotite age of 1732 ± 50 Ma for biotite from a gneiss from east of Saqqaq (age recalculated using the recommended decay constant of Steiger & Jäger 1977). Kalsbeek (1981) obtained a Rb-Sr whole rock isochron age of *c.* 1700 Ma for semipelitic metasediments near the base of the Mârmorilik Formation in the Uummannaq area *c.* 60 km north of the present study area, and Kalsbeek *et al.* (1988) reported a 1760 ± 185 Ma Rb-Sr isochron for siltstones from the early Proterozoic Anap nunâ Group. These ages were interpreted as the time of closure of the K-Ar and Rb-Sr isotope systems after early Proterozoic metamorphism.

An older age for the metamorphism of the Mârmorilik Formation (1911 ± 95 Ma) has been obtained from Pb-Pb isotope data (Kalsbeek *et al.* 1984), and Taylor & Kalsbeek (1990) obtained a Pb-Pb whole-rock isochron age of 1881 ± 20 Ma for marbles of the Mârmorilik Formation.

Two of the new dates from eastern Nuussuaq are of the order of 1750–1800 Ma and may correspond to the time of closure of the K-Ar and Rb-Sr isotope systems in the region during cooling after early Proterozoic metamorphism. The hornblende dates obtained from the slightly deformed diorite collected south of Boye Sø (1861 Ma) and from the amphibolitic inclusion in the gneisses on north-eastern Nuussuaq (1925 Ma) are comparable with the Pb-Pb isochron ages. It is not likely, however, that these dates refer to the peak of early Proterozoic metamorphism since these rocks evidently have undergone the same cooling history as the other samples. More probably, these higher K-Ar ages are due to incorporation of minor amounts of excess argon in the analysed amphiboles.

Naajaat Qaqqaat and Oqaatsut

Three amphibole samples were analysed from Naajaat Qaqqaat. Olive-green hornblende from an amphibolite (GGU 349005) is relatively fresh but contains numerous inclusions of quartz and opaque minerals. This hornblende gave a date of 2285 ± 28 Ma, intermediate between the Archaean age of the Atâ tonalite and the Proterozoic deformation. Similar K-Ar ages which cannot be related to known age information have also been obtained from other parts of the study area.

Hornblende separated from amphibolite sample GGU 349014 is olive green and contains few inclusions. It is relatively fresh although the adjacent plagioclase is almost entirely sericitised and epidotised. The hornblende yielded a Proterozoic date of 1899 ± 24 Ma, which corresponds fairly well with the hornblende and Pb-Pb whole-rock ages obtained from north-eastern Nuussuaq and from the Uummannaq area discussed above.

Pale-green amphibole was obtained from a medium-grained hornblenditic amphibolite (GGU 349053). This sample consists almost entirely of pale-green probably actinolitic hornblende, in a groundmass of biotite and a fine-grained mixture of epidote and chlorite. The amphibole contains few inclusions, mostly of plagioclase, but also minor amounts of biotite are found. The amphibole grains are deformed and often display

Table 2. ^{40}Ar-^{39}Ar analytical data for incremental heating experiments on amphiboles, north-east Disko Bugt and eastern Nuussuaq

Step	$^{40}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	%^{39}Ar cumulated	%$^{40}Ar^*$	Apparent age (Ma ± 1σ)
GGU 349053 (J = 0.001765)						
1	5,246.68	0.289	1.638	0.6	98.17	8105±58
2	4,510.02	0.075	1.873	1.5	99.45	7835±57
3	4,916.11	0.161	0.855	2.2	98.94	7989±57
4	4,354.46	0.233	1.042	2.8	98.28	7773±56
5	1,473.81	0.043	1.920	6.4	99.04	5865±46
6	609.72	0.016	4.976	16.4	99.17	4369±33
7	425.87	0.027	5.530	25.7	97.98	3790±27
8	404.92	0.014	5.911	42.7	98.91	3710±27
9	371.50	0.011	5.978	64.9	99.01	3575±25
10	354.66	0.027	5.858	71.4	97.60	3503±25
11	468.17	0.017	5.936	100.0	98.84	3940±29
GGU 354319 (J = 0.002452)						
1	90.82	0.095	0.770	2.4	75.97	2055±12
2	161.83	0.133	1.567	3.5	80.11	2825±18
3	83.08	0.061	3.032	6.3	81.94	1948±11
4	86.00	0.005	5.005	49.9	98.19	1989±11
5	91.71	0.015	5.060	55.1	95.25	2067±12
6	59.55	0.042	5.241	58.4	82.60	1574± 8
7	63.09	0.048	6.319	61.9	81.31	1636± 9
8	66.11	0.053	6.953	66.1	80.62	1686± 9
9	64.30	0.073	7.187	68.9	74.41	1656± 9
10	71.40	0.015	6.609	100.00	94.02	1772±10
GGU 359139 (J = 0.002479)						
1	48.46	0.067	0.191	11.0	70.53	1378± 7
2	102.35	0.099	0.224	15.7	77.36	2219±13
3	137.15	0.178	1.013	17.7	71.85	2608±16
4	127.82	0.075	4.190	20.8	84.92	2511±15
5	151.18	0.033	8.922	28.7	93.86	2743±17
6	166.92	0.049	9.621	33.3	91.90	2885±19
7	177.83	0.064	11.087	37.0	90.26	2976±20
8	201.89	0.065	12.724	39.7	91.12	3163±21
9	211.37	0.066	13.367	42.3	91.39	3232±22
10	167.39	0.008	10.639	100.0	98.52	2889±19
GGU 352234 (J = 0.001765)						
1	2,081.51	0.400	1.085	0.4	94.07	6468±50
2	580.01	0.082	0.624	1.9	95.59	4287±32
3	265.41	0.076	1.168	3.0	91.39	3065±20
4	175.03	0.033	3.169	8.7	94.17	2477±15
5	192.80	0.023	3.359	14.3	96.29	2609±16
6	210.97	0.012	3.512	25.6	98.11	2734±17
7	206.84	0.019	3.507	32.2	97.03	2707±17
8	215.15	0.012	3.841	39.4	98.17	2762±18
9	216.26	0.030	3.451	43.5	95.71	2769±18
10	219.44	0.015	3.333	48.4	97.81	2790±18
11	219.25	0.027	3.327	52.1	96.12	2789±18
12	225.09	0.003	3.268	100.0	99.62	2826±18

Isotopic ratios corrected for the effects of interfering reactions producing Ar during irradiation.

J is a parameter describing the efficiency of the irradiation of the sample; for details see Faure (1986, pp. 93-96).

%$^{40}Ar^*$ is the percentage of total ^{40}Ar in the sample that is radiogenic.

undulose extinction as well as subgrain formation. Microcracks are common. The amphiboles from this sample yielded a K-Ar date of 4160 ± 34 Ma, which is geologically unrealistic.

In order to investigate this anomalously high K-Ar date, aliquots were irradiated for an ^{40}Ar-^{39}Ar step heating experiment (Fig.2a; Table 2). Very high and geologically unrealistic apparent ages between 8.1 and 5.5 Ga were obtained from the first few steps, representing < 5% of the total ^{39}Ar released (Fig. 2a). The apparent age decreases gradually over the next four steps reaching a minimum of 3503 ± 50 Ma in step 10, followed by an increase in the last step, where a significantly higher age of 3940 ± 58 Ma is obtained. From steps 7 to 10 a weighted mean age of 3644 ± 52 Ma was calculated, which has no geological meaning since it cannot be related to any ages obtained from other parts of the area.

The asymptotic decrease of the apparent age, followed by an increase in the last high temperature step represents a typical saddle-shaped release pattern. This type of pattern is typical for feldspars (e.g. Heizler & Harrison 1988; Harrison 1990; Maluski *et al.* 1990), but has also been described for hornblende (e.g. Lanphere & Dalrymple 1976; Harrison & McDougall 1981; Holm 1991). As demonstrated in this sample, most of the excess Ar component is released at low temperatures, suggesting occupancy of lower activation energy sites within the hornblende (Harrison & McDougall 1981; Maluski *et al.* 1990). Some of the release may, however, come from biotite in the amphibole concentrates, as indicated by the low Ca/K ratios (registered by low $^{37}Ar/^{39}Ar$) in the initial steps (Table 2).

The amphibole from sample 349053 has been subjected to deformation as shown by the strained grains with numerous microcracks. Hornblendes from shear zones commonly take up large quantities of excess argon, and yield discordant spectra (Zeitler 1989). The present sample was collected from a supracrustal amphibolite not far from the strongly sheared contact to the underlying gneissic basement. Furthermore, part of the rock contains substantial amounts of biotite, which could have released Ar at temperatures above *c.* 300°C (the retention temperature of argon in biotite is estimated to be in the range of 280 ± 40°C; Dodson 1973; Harrison & McDougall 1980). Argon released from biotite would have resulted in a significant increase of the partial pressure of Ar within the rock, causing diffusion of this extraneous Ar into microcracks developed in the hornblende during deformation. Furthermore, the Ar pressure in the adjacent gneisses would also have been higher at elevated temperatures during deformation, due to release of Ar from K-rich mineral phases (e.g. biotite and K-feldspar) in the gneisses.

A total gas age of 4330 ± 66 Ma was calculated for all eleven steps in this sample. This age is somewhat higher than the K-Ar age of 4160 ± 34 Ma. This difference is probably caused by sample inhomogeneity.

The four hornblende concentrates from Oqaatsut all come from medium-grained amphibolites located within a mutual distance of about 1 km. Pale blue-green amphiboles separated from samples 349023 and 354328 show clear signs of deformation; they are recrystallised as finer-grained aggregates in a very fine-grained matrix of plagioclase and quartz. These samples yielded dates of 1917 ± 26 Ma and 1870 ± 24 Ma respectively, and demonstrate that Proterozoic metamorphism was accompanied by deformation and shearing, which caused subgrain formation and recrystallisation of the hornblendes.

The amphibole from GGU 354319 is fresh sub- to euhedral, blue-green hornblende with a large number of zircon inclusions. Other mineral phases present are mostly biotite and garnet, indicating an amphibolite facies grade of metamorphism during formation of these amphibolites. The mineral date of 1940 ± 26 Ma obtained from this sample cannot readily be explained as dating the cooling of the hornblende following Proterozoic regional metamorphism, which took place around 1850 Ma (Kalsbeek *et al.* 1984; Taylor & Kalsbeek 1990).

Results of a ^{40}Ar-^{39}Ar age investigation of this sample are listed in Table 2 and the age spectrum obtained is shown in Fig. 2b. The release pattern for this sample is characterised by a first step giving an apparent age of 2055 ± 24 Ma followed by a step yielding a significantly higher date of 2825 ± 36 Ma. Steps 3 to 5 display fairly uniform ages around 1995 Ma. A marked decrease in apparent age to approximately 1700 Ma is observed in the last high temperature steps (6–10).

It is generally agreed to accept as a plateau only adjacent steps (> 3) which represent a large cumulated fraction (> 50%) of the outgassed ^{39}Ar and whose ages differ by no more than a few percent, depending on the analytical uncertainty of each individual age determination. The plateau age is taken as the ^{39}Ar fraction or individual step error weighted average of the individual step ages (Albarede 1982). The age spectrum obtained from this hornblende does not satisfy the criteria referred to above. A weighted mean age of around 1872 Ma for steps 3 to 10 indicates an early Proterozoic age. If this age refers to the crystallisation or total isotopic resetting of the amphibole, it shows that this part of the Disko Bugt area underwent Proterozoic deformation and metamorphism under amphibolite facies conditions.

Blue-green hornblende separated from the fourth sample from Oqaatsut (GGU 354346) also shows marked signs of deformation and incipient recrystallisation. The groundmass consists of minor quartz and feldspar which sometimes are clearly strained and display undulose extinction. Hornblende in this sample often forms intergrowths with smaller biotite grains, and minor biotite and chlorite also occur in the groundmass. An age of 2181 ± 26 Ma was obtained for GGU 354346, considerably older than the other dates obtained from Oqaatsut. This is probably due to the presence of excess Ar in the hornblende of this sample.

Ataa area

Four samples were studied from the Ataa area; two of these represent metagabbroic xenoliths in the Atâ tonalite which, according to Kalsbeek *et al.* (1988), has largely escaped early Proterozoic deformation. An ^{40}Ar-^{39}Ar study was carried out for hornblende from the latter two samples.

Pale olive-green hornblende from one of the xenoliths (GGU 359139) forms sub- to euhedral prismatic grains with only few inclusions. Minor biotite occurs, partly as intergrowths with hornblende. The hornblende yielded a K-Ar date of 2590 ± 30 Ma.

The ^{40}Ar-^{39}Ar release pattern of this sample (Fig. 2c; Table 2) is characterised by a very low apparent age of 1378 ± 14 Ma in the first low temperature step representing 10% of the released ^{39}Ar. The apparent age increases in the second step to 2219 ± 26 Ma. A steep rise in ages occurs from steps 2 to 9, with a maximum of 3232 ± 44 Ma. This part of the age spectrum makes up *c.* 31% of the total ^{39}Ar released. The last high temperature step (10), with 58% of the total ^{39}Ar release, has an apparent age of 2889 ± 38 Ma. This age is somewhat lower than the ages obtained from steps 8 and 9, but agrees with the ages obtained in steps 6 and 7. There is neither an analytical nor a geological explanation for the differences in apparent ages obtained in steps 6, 7 and 10 and those obtained in steps 8 and 9, but it may be related to the break-down of the crystal structure during heating in the Ar-extraction system or by differential degassing of the lattice sites.

A weighted mean age of 2893 ± 38 Ma has been calculated for steps 6, 7 and 10. This age cannot be separated statistically from the age of 2915 ± 38 Ma calculated for steps 6–10, demonstrating that the high ages of steps 8 and 9 only have a minor effect on the calculated weighted mean age. The 2915 Ma age cannot, however, be regarded as a true plateau age, since the steps used in the calculation fail to display a coherent age pattern within a few percent.

Very low Ca/K ratios (low ^{37}Ar/^{39}Ar, Table 2) in steps 1 to 4 indicate that part of the argon release could be derived from degassing of small amounts of biotite present as small inclusions within the hornblende (Rasmussen 1992). This suggestion is supported by a recent investigation by Rex *et al.* (1993) which showed that addition of different amounts of biotite (DR16) to hornblende (MMHb-1) yielded age spectra bearing a striking similarity to 'diffusive loss' profiles.

The ^{40}Ar-^{39}Ar data indicate that the hornblende has retained most of its Ar after incorporation of the inclusion in the Atâ tonalite. The age of 2915 ± 38 Ma obtained from the high temperature steps is somewhat higher than the 2800 Ma age of the Atâ tonalite (Kalsbeek *et al.* 1988; Nutman & Kalsbeek 1999, this volume). The cause of this anomaly is not clear.

The other metagabbroic inclusion (GGU 352234) was sampled from a porphyric granitoid rock on Illuluarsuit Nunataat (Fig. 1), regarded as belonging to a younger intrusive phase of the Atâ tonalite (L. Skjernaa, personal communication 1992). Hornblende from this sample is sub- to euhedral, and inclusions of quartz are common; it looks fresh and contains only few microcracks. Small amounts of biotite are present in the rock, sometimes occurring as inclusions in the hornblende. The hornblende yielded a K-Ar date of 2750 ± 30 Ma. It is likely that the K-Ar system was reset during emplacement of the tonalite, and the age is interpreted as representing the time at which the intrusion cooled below the Ar retention temperature of hornblende.

To test the validity of this date and to detect a possible component of excess ^{40}Ar, a step heating ^{40}Ar-^{39}Ar experiment was performed (Table 2). The ^{40}Ar-^{39}Ar age spectrum (Fig. 2d) shows a rather simple release pattern, characterised by yielding unrealistically high apparent ages for the first three steps, representing *c.* 2% of the total ^{39}Ar released. The highest age of 6468 ± 100 Ma, calculated for the first step, gradually decreases to 3065 ± 40 Ma in the third step. High apparent age steps as these can either be produced as a consequence of recoil of ^{39}Ar during the irradiation process, or they can represent excess argon in the mineral. The rest of the ^{40}Ar-^{39}Ar release pattern is typical of a mineral that has suffered partial argon loss by diffusion. This pattern is characterised by a relatively low age of 2477 ± 30 Ma in step 4, followed by a gradual increase in age, reaching an almost constant level at approximately 2800 Ma.

The sample displays a Ca/K distribution (registered by $^{37}Ar/^{39}Ar$, Table 2) that indicates presence of biotite influencing the low temperature steps of the age spectrum (Rasmussen 1992), in accordance with observations by Rex *et al.* (1993).

The total ^{40}Ar-^{39}Ar age of 2855 ± 36 Ma calculated for this sample is 3.8% higher than the date of 2750 ± 30 Ma obtained from the conventional K-Ar age determination. This difference can be explained by some degree of recoil effect of ^{39}Ar in the low activation energy sites within the hornblende, thus producing higher ^{40}Ar-^{39}Ar ratios resulting in high apparent ages without geological significance.

Steps 6 to 12 form a coherent pattern, comprising *c.* 85% of the total cumulated ^{39}Ar released, and satisfy the criteria for defining an age plateau (Albarede 1982). The weighted mean plateau age of 2793 ± 36 Ma conforms within the limits of analytical error with the age of *c.* 2800 Ma obtained for the Atâ tonalite (Kalsbeek *et al.* 1988; Nutman & Kalsbeek 1999, this volume). The hornblende plateau age is therefore interpreted as representing the time at which the intrusion cooled below the Ar retention temperature of the hornblende. Even if the xenolith was very large, it is unlikely that the hornblende could have retained any of its former content of radiogenic argon, since the intrusion temperature of the granite (700–800°C) is significantly higher than the retention temperature of Ar in hornblende (530 ± 40°C; Harrison & McDougall 1980). The ^{40}Ar-^{39}Ar age spectrum further indicates that during later Proterozoic deformation temperatures in this part of the area were not sufficiently high to induce significant diffusive loss of argon from the hornblende, but that the biotite inclusions were affected. This means that the Proterozoic metamorphic grade in this part of the area never reached more than greenschist facies conditions.

Well-preserved brownish-green, anhedral hornblende was separated from a black amphibolite (GGU 272611) occurring within dioritic gneiss in the southern part of Arveprinsen Ejland. It is almost free of inclusions and contains only few microcracks. Plagioclase in this sample is fresh and only displays signs of incipient carbonisation. The hornblende yielded a date of 2457 ± 28 Ma.

A similar intermediate date of 2292 ± 28 Ma was obtained from a basic inclusion (GGU 352239) in a migmatitic gneiss at Oqaatsunnguit. The olive-green hornblende obtained from this rock contains some minor inclusions of quartz and biotite. It contains numerous microcracks. Since these samples have not been investigated using the ^{40}Ar-^{39}Ar method, detailed interpretation of the dates is not possible. Either the K-Ar systems were only partly reset during early Proterozoic tectono-thermal activity, or, if total resetting has taken place, the hornblende contains significant proportions of excess argon.

Eastern Disko Bugt

A pale green hornblende from a medium-grained amphibolite (GGU 355612) in supracrustal rocks at Nunatarsuaq (Fig. 1) yielded a K-Ar date of 1948 ± 26 Ma. The large crystalloblastic amphiboles in this sample form sub- to euhedral, inclusion-free grains. No retrograde mineral assemblages were observed and the associated plagioclase only shows weak signs of sericitisation.

This date is considerably older than the K-Ar biotite age of 1725 ± 30 Ma obtained by Larsen & Møller (1968) from the gneisses near Jakobshavn/Ilulissat. It is also older than the peak of early Proterozoic metamorphism, at *c.* 1850 Ma (Kalsbeek *et al.* 1984; Taylor & Kalsbeek 1990). It is not clear whether the 1948 Ma date refers to Proterozoic metamorphism earlier than 1850 Ma in this part of the area or if the date is related to a component of excess Ar in *c.* 1850 Ma hornblende.

Lamproite at Oqaatsunnguit

A lamproite stock with coarse-grained ellipsoidal phlogopite nodules, *c.* 1 cm in diameter, intruded in rocks of the Atâ tonalite at Oqaatsunnguit (Fig. 1), has been described by Skjernaa (1992). The nodules are monomineralic, dark brown, and consist of phlogopite with a central grain completely surrounded by a concentrically arranged mantle grain, giving the nodules an ellipsoidal appearance. A K-Ar date of 1764 ± 24 Ma was obtained for this phlogopite (GGU 343955), in excellent agreement with the 1743 ± 70 Ma K-Ar age on matrix phlogopite from the same lamproite (Larsen & Rex 1992). The agreement between the K-Ar ages obtained for the coarse-grained phlogopite nodules and the fine-grained matrix phlogopite indicates that the ages represent the crystallisation of the lamproite, and that the K-Ar system has not been significantly affected since then. The correspondence of the two ages also indicates that the lamproite stock must have been emplaced at a high level in the crust, since significant radiogenic ^{40}Ar loss after crystallisation would be expected (especially from the phlogopite in the matrix because of the smaller grain size) if temperatures had been significantly above the closure temperature of the phlogopite-biotite K-Ar system (*c.* 280°C, e.g. Harrison & McDougall 1980) for a long time after crystallisation.

Summary and conclusions

Regional investigations have shown that the metamorphic grade of the Archaean supracrustal rocks in the Ataa region range from upper greenschist to amphibolite facies (Garde & Steenfelt 1999, this volume). The presence of kyanite, staurolite, garnet, biotite and hornblende at Naujaat Qaqqaat and Oqaatsut makes it possible to estimate metamorphic *P* and *T* levels of at least 5–7 kb and 500–625°C (Winkler 1979; Apted & Liou 1983) for the formation of the dominant mineral assemblages in these two areas.

K-Ar and ^{40}Ar-^{39}Ar age investigations from Naujaat Qaqqaat and Oqaatsut revealed no reliable Archaean hornblende dates. There are two likely explanations of the Proterozoic K-Ar hornblende dates from the two areas. The first explanation is that the temperatures reached during the Proterozoic tectono-thermal event were not sufficiently high, or conditions were too dry, for recrystallisation of the hornblende of an earlier Archaean metamorphic event, but reached temperatures high enough to reset the K-Ar hornblende system. However, amphiboles are usually considered as the most retentive of the minerals used for K-Ar dating, and it has been argued that recrystallisation may be necessary to reset hornblende ages totally (Dallmeyer 1979). The other explanation is that the Proterozoic tectono-thermal reworking reached amphibolite facies grade resulting in either total recrystallisation of the hornblendes or partial modification by dynamic grain-size reduction eventually resulting in crystallisation of fine-grained hornblende aggregates, which has been observed in a number of samples. The consequence of these grain modifications is a total resetting of the K-Ar hornblende clock. The indication of a total resetting by grain-size reduction and recrystallisation is sustained by the rather flat ^{40}Ar-^{39}Ar age spectrum obtained from sample GGU 354319, which yielded Proterozoic ages for over 95% of the total ^{39}Ar released (Fig. 2b). The large spread in K-Ar mineral dates (> 300 Ma) over relatively short distances in the two areas is probably due to incorporation of variable amounts of excess ^{40}Ar in the hornblendes, which has variably raised their bulk ages, as indicated by the ^{40}Ar-^{39}Ar saddle shaped spectrum obtained from GGU 349053 (Fig. 2a). It is therefore clear that Proterozoic deformation and metamorphism have played an important role at Naujaat Qaqqaat and Oqaatsut.

The two age spectra obtained from the inclusions in the Atâ tonalite (GGU 359139 and 352234, Figs 2c, d) demonstrate that in the Ataa area temperatures were not high enough to reset the hornblende ages during Proterozoic reworking. These age spectra also show the influence of biotite contamination in the low temperature steps, in accordance with observations by Rex *et al.* (1993). The calculated average ages for these two samples reflect the time at which the xenoliths together with the surrounding rocks cooled below the retention temperature of the hornblende (*c.* 500–570°C; Harrison 1981).

The date of 1948 ± 26 Ma obtained from the eastern part of the Disko Bugt region suggests that also in this part of the area Proterozoic tectono-thermal reworking provided conditions under which the K-Ar system behaved as an open system.

The dates obtained from north-eastern Nuussuaq (1925 ± 24 Ma and 1751 ± 24 Ma), from central eastern Nuussuaq (1861 ± 26 Ma) and from the Saqqaq area (1789 ± 24 Ma) show that Proterozoic tectono-thermal reworking has taken place in these areas.

The high degree of conformity between the phlogopite mineral ages obtained in this study (1764 ± 24 Ma) and those presented by Larsen & Rex (1992; 1743 ± 70 Ma) indicates that these ages can be interpreted as representing the time of intrusion of the lamproites in the region.

Acknowledgements

Thanks to Feiko Kalsbeek, Agnete Steenfelt, Adam A. Garde and Lilian Skjernaa for providing sample material for this isotopic work. Feiko Kalsbeek is thanked for help with the manuscript, and D.C. Rex for helpful comments on the ^{40}Ar-^{39}Ar age investigations and for reviewing the manuscript.

References

Albarede, F. 1982: The $^{39}Ar/^{40}Ar$ technique of dating. In: Odin, G.S. (ed.): Numerical dating in stratigraphy, 181–197. Chichester, UK: Wiley.

Apted, M.J. & Liou, J.G. 1983: Phase relations among greenschist, epidote-amphibolite and amphibolite in a basaltic system. American Journal of Science **283-A**, 328–354.

Dallmeyer, R.D. 1979: $^{40}Ar/^{39}Ar$ dating: principles, techniques and applications in orogenic terranes. In: Jäger, E. & Hunziker, J.C. (eds): Lectures in isotope geology, 77–104. Berlin: Springer-Verlag.

Dodson, M.H. 1973: Closure temperature in cooling geochronological and petrological systems. Contributions to Mineralogy and Petrology **40**, 259–274.

Faure, G. 1986: Principles of isotope geology, 589 pp. New York: Wiley & Sons.

Garde, A.A. & Steenfelt, A. 1999: Precambrian geology of Nuussuaq and the area north-east of Disko Bugt, West Greenland. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 6–40 (this volume).

Harrison, T.M. 1981: Diffusion of ^{40}Ar in hornblende. Contributions to Mineralogy and Petrology **78**, 324–331.

Harrison, T.M. 1990: Some observations on the interpretation of feldspar $^{40}Ar/^{39}Ar$ results. Chemical Geology (Isotope Geoscience Section) **80**, 219–229.

Harrison, T.M. & McDougall, I. 1980: Investigations of an intrusive contact, north-west Nelson, New Zealand – I. Thermal, chronological and isotopic constraints. Geochimica et Cosmochimica Acta **44**, 1985–2003.

Harrison, T.M. & McDougall, I. 1981: Excess ^{40}Ar in metamorphic rocks from Broken Hill, New South Wales: implications for $^{40}Ar/^{39}$ Ar age spectra and the thermal history of the region. Earth and Planetary Science Letters **55**, 123–149.

Heizler, M.T. & Harrison, T.M. 1988: Multiple trapped argon isotope components revealed by $^{40}Ar/^{39}Ar$ isochron analysis. Geochimica et Cosmochimica Acta **52**, 1295–1303.

Holm, P.M. 1991: Radiometric age determinations in the Kærven area, Kangerdlugssuaq, East Greenland Tertiary igneous Province: $^{40}Ar/^{39}Ar$, K/Ar and Rb/Sr isotope results. Bulletin of the Geological Society of Denmark **38**, 183–201.

Kalsbeek, F. 1981: The northward extent of the Archaean basement of Greenland – a review of Rb-Sr whole-rock ages. Precambrian Research **14**, 203–219.

Kalsbeek, F., Taylor, P.N. & Henriksen, N. 1984: Age of rocks, structures and metamorphism in the Nagssugtoqidian mobile belt, West Greenland – field and Pb-isotope evidence. Canadian Journal of Earth Sciences **21**, 1126–1131.

Kalsbeek, F., Taylor, P.N. & Pidgeon, R.T. 1988: Unreworked Archaean basement and Proterozoic supracrustal rocks from northeastern Disko Bugt, West Greenland: implications for the nature of Proterozoic mobile belts in Greenland. Canadian Journal of Earth Sciences **25**, 773–782.

Lanphere, M.A. & Dalrymple, G.B. 1976: Identification of excess ^{40}Ar by the $^{40}Ar/^{39}Ar$ age spectrum technique. Earth and Planetary Science Letters **32**, 141–148.

Larsen, L.M. & Rex, D.C. 1992: A review of the 2500 Ma span of alkaline-ultramafic, potassic and carbonatitic magmatism in West Greenland. Lithos **28**, 367–402.

Larsen, O. & Møller, J. 1968: Potassium-argon age studies in West Greenland. Canadian Journal of Earth Sciences **5**, 683–691.

Maluski, H., Monie, P., Kienast, J.R. & Rahmani, A. 1990: Location of extraneous argon in granulitic-facies minerals: a paired microprobe-laser probe $^{40}Ar/^{39}Ar$ analysis. Chemical Geology (Isotope Geoscience Section) **80**, 193–217.

Nutman, A.P. & Kalsbeek, F. 1999: SHRIMP U-Pb zircon ages for Archaean granitoid rocks, Ataa area, north-east Disko Bugt. In: Kalsbeek, F. (ed.): Precambrian geology of the Disko Bugt region, West Greenland. Geology of Greenland Survey Bulletin **181**, 49–54 (this volume).

Rasmussen, H. 1992: Petrography, geochemistry and combined K/Ar and $^{40}Ar/^{39}Ar$ mineral age investigations of Archaean amphibolitic, ultramafic and related supracrustal rocks from Naujât qáqât and Oqaitsut, Disko Bugt, West Greenland, 149 pp. Unpublished cand. scient. thesis, University of Copenhagen, Denmark.

Rex, D.C., Guise, P.G. & Wartho, J.-A. 1993: Disturbed ^{40}Ar-^{39}Ar spectra from hornblendes: thermal loss or contamination? Chemical Geology (Isotope Geoscience Section) **103**, 271–281.

Skjernaa, L. 1992: A lamproite stock with ellipsoidal phlogopite nodules at Oqaitsúnguit, Disko Bugt, central West Greenland. Rapport Grønlands Geologiske Undersøgelse **154**, 33–47.

Steiger, R.H. & Jäger, E. 1977: Subcommision on Geochronology: Convention on the use of decay constants in geo- and cosmochronology. Earth and Planetary Science Letters **36**, 369–362.

Taylor, P.N. & Kalsbeek, F. 1990: Dating the metamorphism of Precambrian marbles: examples from Proterozoic mobile belts in Greenland. Chemical Geology (Isotope Geoscience Section) **86**, 21–28.

Winkler, H.G.F. 1979: Petrogenesis of metamorphic rocks, 338 pp. New York: Springer-Verlag.

Zeitler, P.K. 1989: The geochronology of metamorphic processes. In: Daly, J.S., Cliff, R.A. & Yardley, B.W.D. (eds): Evolution of metamorphic belts. Geological Society Special Publication (London) **43**, 131–147.