Archaean age and Proterozoic metamorphic overprinting of the crystalline basement at Victoria Fjord, North Greenland

Bent Tauber Hansen, Feiko Kalsbeek and Paul Martin Holm

Zircon U-Pb and Rb-Sr whole-rock isotope data show that the crystalline rocks at the head of Victoria Fjord, North Greenland, have Archaean ages (*c.* 3000 Ma), but that strong disturbance of the isotope systems has taken place later. K-Ar analyses on hornblende show that the area underwent a phase of high-grade metamorphism during the Proterozoic, probably around 1850 Ma.

B. T. H., Institut für Mineralogie, Westfälische Wilhelms-Universität, Corrensstrasse 24, D-4400 Münster, West Germany.
F. K., Grønlands Geologiske Undersøgelse, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.
P. M. H., Institut for Petrologi, Københavns Universitet, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.

Large areas of the crystalline shield of Greenland consist of Archaean rocks, locally interrupted by Proterozoic intrusions, and commonly affected by Proterozoic tectonometamorphic activity (Kalsbeek, 1986; fig. 1). In North Greenland the crystalline basement is only exposed at the head of Victoria Fjord along the margin of the Inland Ice; elsewhere ice-transported boulders of basement rocks are common in glacial deposits, and indicate the presence of crystalline rocks beneath the northern sector of the Inland Ice and probably also underlying the Middle Proterozoic to Lower Palaeozoic platform throughout North Greenland.

This report presents the results of U-Pb age determinations on zircons from two samples, Rb-Sr whole-rock isotope data on two sample sets, and K-Ar measurements on three hornblende concentrates, all from the basement rocks at the head of Victoria Fjord. The samples were collected in 1984 by Niels Henriksen and Hans F. Jepsen (GGU) and the following description of the field setting of the rocks is based on their field observations (Henriksen & Jepsen, 1985).

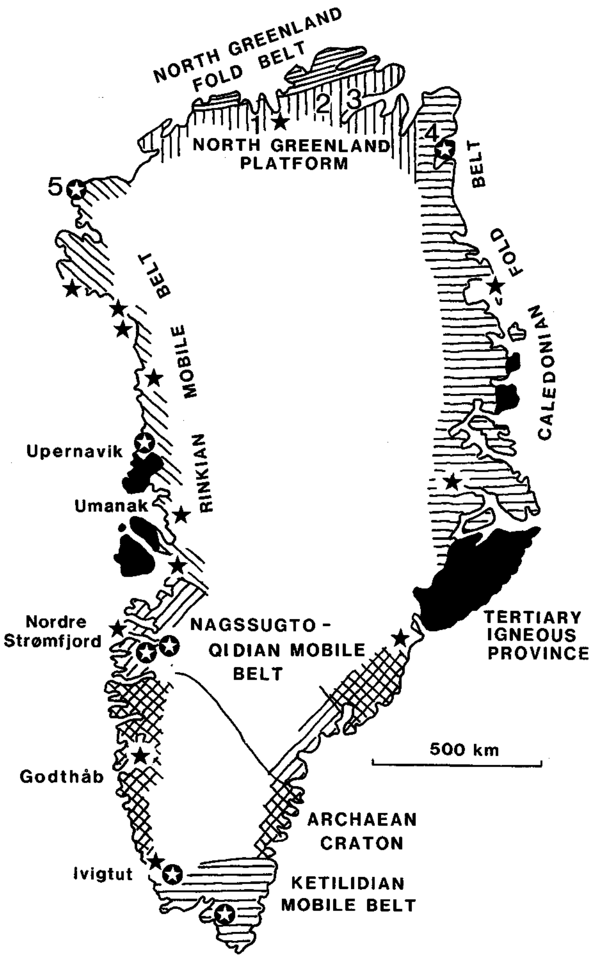


Fig. 1. The main tectonic units of Greenland, with localities of dated Archaean and Proterozoic rocks (black and white stars, respectively), after Kalsbeek (1986). Localities and rock units mentioned in the text are numbered. 1: Head of Victoria Fjord, where the samples for the present investigation were collected. 2: Sydpasset. 3: Independence Fjord. 4: Ingolf Fjord. 5: The Etah meta-igneous complex of Inglefield Land.

The crystalline basement at Victoria Fjord

Crystalline rocks outcrop at the head of Victoria Fjord over an area of *c.* 20 × 30 km, centred at approximately 81° 30′N 45° 30′W. They are unconformably overlain by flat lying sediments of the Moræneso̸ (late Proterozoic) and Portfjeld (Cambrian) Formations, indicating a Precambrian age for the basement. The exposed rocks are dominated by homogeneous leucocratic orthogneisses with variable intensity of foliation and grading locally into almost granitic rocks. The rocks are often migmatitic; they may contain thin quartzo-feldspathic veins conformable to the foliation of the gneisses, and pegmatites occur locally both as conformable veins and as later cross-cutting dyke-like bodies. The orthogneisses contain numerous sheets of black amphibolite, up to 30 m wide, which locally are discordant to the gneissic foliation and are thought to represent former basic intrusions. Supracrustal rocks have been observed at a number of localities within the orthogneisses. They are dominated by foliated amphibolite bands together with biotite-rich mica schists and, at one locality, by a coarsely crystalline marble layer. Their thickness varies up to *c.* 50 m. At one locality an irregularly shaped body of late leucocratic quartz diorite was found with locally sharp and also locally gradational boundaries with the surrounding foliated orthogneiss.

Most of the samples studied were collected at the south-western corner of a nunatak near the edge of the Inland Ice (81° 31′N 44° 45′W); one sample used for hornblende K-Ar dating (314237) comes from another nunatak (81° 25′N 45° 05′W).

Zircon U-Pb data

Zircon concentrates were prepared from one sample of the homogeneous orthogneisses (GGU 312632) and one sample of the late quartz diorite (GGU 312635). The gneiss sample consists of about equal proportions of quartz, plagioclase (oligoclase) and K-feldspar, with some biotite (partly chloritised), and accessory apatite, epidote, opaque minerals, sphene and zircon. The quartz diorite consists mainly of clouded plagioclase (andesine) with quartz and biotite (strongly chloritised) and accessory apatite, opaque minerals and zircon. This sample has a well preserved igneous texture.

Analytical procedures

The zircon U-Pb work was carried out at the Zentrallaboratorium für Geochronologie at the University of Münster, West Germany. The chemical procedures for the zircon analyses followed the method of Krogh (1973). A more detailed description of the method applied is given by Persson *et al.* (1983). The isotopic measurements were carried out on a Teledyne 12" 90° solid-source mass-spectrometer. For the common lead correction an isotopic composition corresponding to the upper concordia intercept ages, computed according to the model of Stacey & Kramers (1975), was employed. The assigned analytical errors (2σ) based on replicate analyses are 0.7% for the $^{207}Pb/^{235}U$ ratios and 0.4% for the $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ratios. Throughout this paper we use the decay constants recommended by the IUGS (Steiger & Jäger, 1977), and the precisions of the age results are given at the two sigma (95%) level of confidence. The least squares method of York (1969) was used for the calculation of the regression lines.

Results

Most of the zircons of gneiss sample 312632 are elongate prismatic with a length–width ratio of 3 to 4, and have a light grey colour. They mostly have round edges and blunt terminations. Other grains are more strongly rounded and have a brownish colour. Only a few grains have cracks, but many display corroded surfaces. The proportion of long prismatic to rounded grains is about 2 to 1, slightly increasing with decreasing grain size.

Analytical data for five grain-size fractions are listed in Table 1 and shown graphically in fig. 2A. The zircons are highly discordant and, apart from the size fraction $< 40\mu$, show little variation in their isotopic composition. There is no significant correlation between the uranium contents of the different analysed fractions and their grain size (Table 1), a phenomenon often found in other zircons from Archaean rocks (Hansen *et al.*, in press). The data points do not define an ideal chord (fig. 2A) but scatter around a reference line (MSWD: 2.3) with an upper intercept corresponding to an age of 2863^{+32}_{-30} Ma, and a lower intercept at 72 ± 44 Ma. The regression line is strongly affected by the fraction $< 40\mu$; if this point is omitted from the regression calculation the upper intercept age becomes *c.* 2750 Ma.

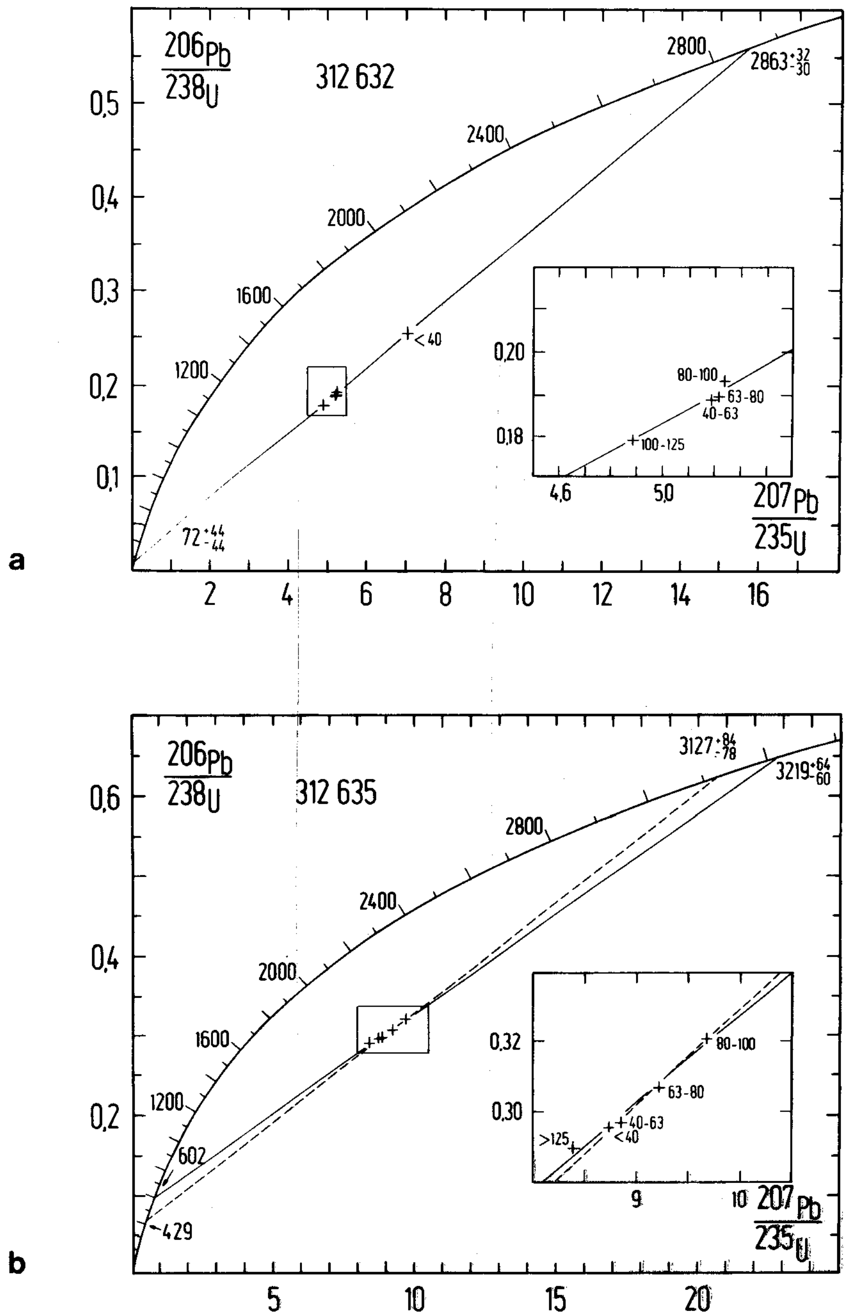


Fig. 2. Zircon concordia plots for samples 312632 and 312635 from the Victoria Fjord basement. The upper and lower intersection ages and the ages shown along the concordia line are in Ma, and the small numbers that identify the data points give the zircon size fractions in microns.

Table 1. U-Pb analytical data on zircons from the crystalline basement at the head of Victoria Fjord, North Greenland

GGU sample No & sieve fraction in μm	g sample analysed	Observed atomic ratios $\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{207}Pb}{^{206}Pb}$	$\frac{^{206}Pb}{^{204}Pb}$	U ppm	Pb_{rad} ppm	$^{206}Pb_{rad}$ n mol/g	Atomic ratios corrected for blank* and common Pb $\frac{^{206}Pb}{^{238}U}$	$\frac{^{207}Pb}{^{235}U}$	$\frac{^{207}Pb}{^{206}Pb}$	Apparent age Ma $\frac{^{207}Pb}{^{206}Pb}$
GGU 312632											
< 40	0.0060	0.79183	0.41810	54.1	1074	339	1137	0.25369	7.031	0.20100	2834
40 – 63	0.0064	0.17843	0.23280	349	2912	609	2296	0.18900	5.187	0.19904	2818
63 – 80	0.0040	0.18112	0.23279	352	1875	395	1484	0.18980	5.216	0.19932	2821
80 – 100	0.0048	0.17553	0.22899	362	1527	326	1232	0.19339	5.237	0.19642	2797
100 – 125	0.0038	0.18361	0.23162	349	1603	319	1197	0.17909	4.886	0.19786	2809
GGU 312635											
< 40	0.0051	0.13858	0.23977	457	944	308	1164	0.29555	8.739	0.21444	2939
40 – 63	0.0056	0.12723	0.23873	514	980	321	1214	0.29695	8.855	0.21626	2953
63 – 80	0.0060	0.12088	0.23970	531	908	306	1162	0.30671	9.218	0.21799	2966
80 – 100	0.0054	0.11711	0.23792	605	930	329	1244	0.32066	9.678	0.21890	2973
> 125	0.0074	0.14118	0.23431	483	1034	331	1249	0.28969	8.397	0.21023	2907

Composition of lead used for blank correction: $^{206}Pb/^{204}Pb$ = 18.7, $^{207}Pb/^{204}Pb$ = 15.63, $^{208}Pb/^{204}Pb$ = 38.63. The composition of common lead used for the correction follows the model of Stacey & Kramers (1975).

The $^{207}Pb/^{206}Pb$ ages for the different zircon fractions are in the order of 2800 Ma, and this must be regarded as the minimum age of zircon formation in sample 312632.

The zircons of sample 312635 (the late quartz diorite) have a light brown colour and a length–width ratio of about 2. All grains show cracks and rounded terminations, and most have pitted surfaces. In the two fractions < 63μ a minor proportion of the grains are transparent, free of inclusions and are elongate prismatic with well developed terminations.

The data of five analysed size fractions scatter around a chord (MSWD: 2.9) which intersects with concordia at 3219^{+64}_{-60} Ma and 602 ± 95 Ma (fig. 2B). The coarsest fraction, which is also the most uranium-rich (Table 1), yields the most discordant point, whereas the other fractions show increasing discordance with decreasing grain size. If the data point for the coarsest fraction is omitted from the calculation of the discordia, an upper intersection age of 3127^{+84}_{-78} Ma is obtained. Because of the high discordance of the data points the extended extrapolation does not allow precise dating of the rock. However, the $^{207}Pb/^{206}Pb$ ages show lead components as old as 2973 Ma (Table 1) which must be regarded as a minimum age for the formation of the zircons.

Discussion

The zircon U-Pb data show beyond doubt that the rocks in question have Archaean ages. A more detailed interpretation of the data is not straightforward, however. The field evidence shows that the late quartz diorite (GGU 312635) is younger than the homogeneous foliated orthogneisses (GGU 312632). Nevertheless, the orthogneiss zircons yield a younger age (*c.* 2860 Ma) than those of the leucogranite (*c.* 3200 Ma). This shows that the zircon ages cannot be taken at face value. It seems likely that the zircon U-Pb systems have undergone a complex multistage history, with different episodes of lead loss and/or new growth of zircon, to give rise to this inconsistency. Under such circumstances the information obtained from the zircon U-Pb data is considerably reduced in detail. The Rb-Sr analyses reported in the next section were carried out to obtain further information on the history of the rocks.

Rb-Sr whole-rock data

Rb-Sr isotope analyses were carried out on two sets of orthogneiss samples collected within a short distance. One set consists of slightly banded orthogneisses, whereas the gneisses of the other set are more homogeneous. The latter were collected from large, angular, ice-transported boulders, apparently derived from a near-by source.

Analytical procedure

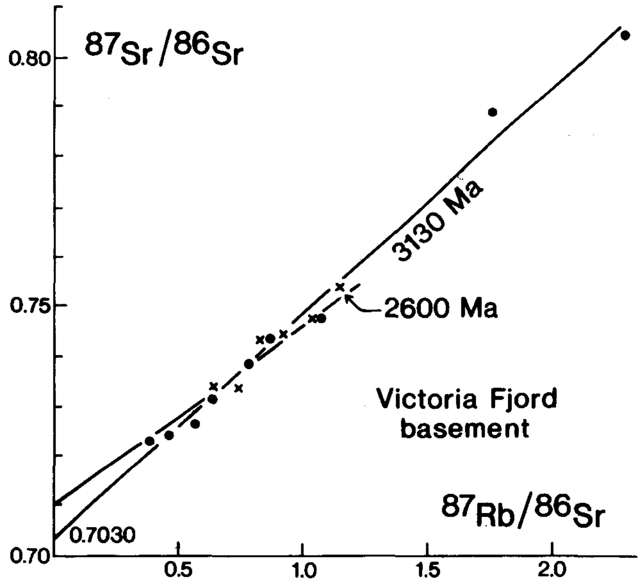
The Rb-Sr isotope work was carried out at the Institut for Petrologi, University of Copenhagen. Strontium was separated from the samples by conventional ion-exchange techniques, and its isotopic composition was measured with a Varian Mat solid source mass-spectrometer with on-line data reduction. The $^{87}Sr/^{86}Sr$ ratios were normalised and calibrated against a value of 0.7080 for the Eimer and Amend $SrCO_3$ standard. Rb/Sr ratios were measured by XRF spectrometry and calibrated against USGS rock standards. The isochron calculations were performed by the McIntyre *et al.* (1966) method, model 1, using the following (1σ) precisions: 1% for the $^{87}Rb/^{86}Sr$ ratios and 0.0002 for the $^{87}Sr/^{86}Sr$ ratios. The errors associated with the age and initial $^{87}Sr/^{86}Sr$ ratios were calculated by multiplying the McIntyre model 1 errors with the square root of the MSWD values obtained.

Table 2. Rb-Sr isotope data for granitic gneisses in the crystalline basement at the head of Victoria Fjord, North Greenland

Sample No.	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
A 312617	118	598	0.568	0.7259
312620	96	441	0.631	0.7315
312621	107	361	0.862	0.7433
312622	96	351	0.786	0.7385
312623	156	257	1.746	0.7891
312624	139	368	1.078	0.7473
312627	74	460	0.462	0.7239
312628	60	453	0.383	0.7227
312630	111	139	2.295	0.8050
B 312643	125	345	1.035	0.7472
312644	98	305	0.928	0.7447
312647	108	376	0.824	0.7433
312650	113	287	1.143	0.7539
312651	106	409	0.743	0.7400
312652	85	382	0.637	0.7335

A: slightly inhomogeneous orthogneisses (sample set 1); B: homogeneous orthogneisses (sample set 2). Rb and Sr (in ppm, by XRF) ± *c.* 5–10%. Precisions for $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ are estimated at *c.* 1% and *c.* 0.0002 (1σ), respectively.

Fig. 3. Rb-Sr isochron plot for gneisses from the Victoria Fjord basement. The dots represent slightly banded gneisses of sample set 1 and the crosses the more homogeneous gneisses of sample set 2 (see the text).



Results

The samples of the banded gneisses of the first set have a relatively wide range in Rb/Sr ratios and nine samples were selected for Sr-isotope measurements (Table 2). They provide a poorly fitted isochron (MSWD 44) giving an age of 3130 ± 380 Ma and an initial $^{87}Sr/^{86}Sr$ ratio (Sr_i) of 0.7030 ± 0.0039 (fig. 3).

The more homogeneous gneisses from the second sample set have a narrower range of Rb/Sr ratios. Six samples were selected for Sr-isotopic analysis; they yield a poor isochron (MSWD 21). The age associated with this isochron is very poorly defined: 2600 ± 670 Ma, Sr_i 0.7106 ± 0.0080, partly because of the scatter about the isochron and partly because of the restricted range in $^{87}Rb/^{86}Sr$ ratios. A regression of all samples from both sets yields an age of 3120 ± 310 Ma, Sr_i 0.7034 ± 0.0033 and MSWD 36.

Discussion

Because of the large scatter of the Rb-Sr isotope data about the isochrons, the ages obtained are poorly defined. However, the data confirm the Archaean age of the rocks derived from the zircon U-Pb measurements.

The scatter itself is consistent with a strong disturbance of the isotope systems in the rocks after their initial formation, as already suggested by the zircon U-Pb data. Such later disturbance often leads to a lowering of the Rb-Sr isochron ages, and sample sets with a narrow range of Rb/Sr ratios commonly yield lower apparent ages, and higher Sr_i values, than sample sets with a wider range of Rb/Sr ratios (Kalsbeek & Pidgeon, 1980). The lower apparent age obtained for the homogeneous orthogneisses is in agreement with this behaviour.

It is not possible from the Rb-Sr data to deduct the time of this disturbance. However, major tectonometamorphic events in the Greenland shield took place in the late Archaean, until c. 2600 Ma, and during the Proterozoic, around 1850 Ma ago (Kalsbeek & Pidgeon, 1980; Kalsbeek *et al.* 1984), and one or both of these may be responsible for the isotopic disturbances observed in the investigated rocks. In rocks of the Archaean craton which have been affected by late Archaean events, but not by Proterozoic metamorphism, isochron relationships are normally much better preserved (resulting in lower MSWD values) than in Archaean rocks in areas affected by Proterozoic metamorphism (Kalsbeek & Pidgeon, 1980; Kalsbeek, 1981). The high MSWD values, from 20 to 45, obtained for the gneisses from the Victoria Fjord area, suggest therefore that the isotopic disturbance in question is due to a Proterozoic rather than a late Archaean event. K-Ar mineral analyses (next section) have been carried out to test this impression.

K-Ar hornblende data

K-Ar analyses were carried out on hornblende concentrates from three samples of the amphibolites that form sheets in the gneisses, and that are thought to represent former intrusions (see above). The analytical work was done at the Institut for Petrologi, University of Copenhagen; the analytical procedures have been described by Pedersen & Holm (1983). The data obtained are given in Table 3.

Results and discussion

The apparent ages calculated from the analytical data are 1983 ± 30 Ma, 1827 ± 27 Ma, and 1903 ± 40 Ma. Two of these are within error the same as the age for the peak of Proterozoic metamorphism in the Nagssugtoqidian and Rinkian mobile belts, 1880 ± 50 Ma, obtained by Kalsbeek *et al.* (1984), and it is thus natural to correlate the K-Ar ages with a phase of metamorphism roughly contemporaneous with the Proterozoic metamorphism farther south. It appears likely that this metamorphism was the main cause of the disturbance of the zircon U-Pb and whole-rock Rb-Sr isotope systems noted above. The third K-Ar date is slightly higher (1983 ± 30 Ma). This may be due to a minor proportion of radiogenic argon not expelled during the Proterozoic metamorphism, or to the presence of some 'excess' argon from foreign sources incorporated during the metamorphism.

Table 3. K-Ar isotope data for three hornblende concentrates from amphibolite sheets in the crystalline basement at the head of Victoria Fjord, North Greenland

Sample No.	K weight %	Ar 10^{-10} mol/g	Ar_{rad} %	Apparent age Ma
312633	0.607	38.00	81.47	1983 ± 30
312634	0.754	41.35	81.10	1827 ± 27
314237	0.889	52.06	83.66	1903 ± 40

Estimated precisions: K – *c.* 0.8%, total Ar – *c.* 0.2%, and radiogenic Ar (Ar_{rad}) – *c.* 0.6%, all relative to the measured concentrations.

Regional correlation

The presence of Archaean rocks in the basement beneath the North Greenland platform has earlier been suggested by Kalsbeek & Jepsen (1980) from a Rb-Sr isotope study of ice-transported boulders from Independence Fjord (locality 3, fig. 1) and of samples from a giant gneiss inclusion within a Proterozoic dolerite at Sydpasset (loc. 2, fig. 1). Later (probably Proterozoic) disturbance of the Rb-Sr isotope systems of these rocks was evident, however, and the Rb-Sr data did not, therefore, give reliable age information. The most important result of the present investigation is that it provides definitive proof of the existence of Archaean rocks in northernmost Greenland, and of the overprinting of these rocks by a phase of Proterozoic metamorphism.

The structure of the northernmost part of the crystalline shield of Greenland is not clear. Fig. 1 shows the presence of proven Archaean rocks (black stars) north of the Archaean craton of South Greenland. The area north of Upernavik in West Greenland contains an Archaean basement, overlain, in part, by Proterozoic supracrustal rocks (Kalsbeek, 1986). However, in northernmost West Greenland (loc. 5, fig. 1) the Etah meta-igneous complex is of Proterozoic age (*c.* 1850 Ma), and according to the Rb-Sr evidence these rocks probably represent newly formed Proterozoic crust, and not reworked Archaean material (P. R. Dawes, F. Kalsbeek and O. Larsen, unpublished data). Equally, in northernmost East Greenland, near Wegener Øer in Ingolf Fjord (loc. 4, fig. 1), Proterozoic rocks have been found (*c.* 2000 Ma, zircon U-Pb data, R. T. Pidgeon, personal communication, 1981). The Rb-Sr isotope systems in these rocks are strongly disturbed (F. Kalsbeek, unpublished data), probably during the Caledonian orogeny. Here also, there is no isotopic evidence to suggest that these rocks might be reworked Archaean material.

Farther south in East Greenland, undoubted Archaean rocks have again been found (e.g. Steiger *et al.*, 1976; for summary see Kalsbeek, 1981). Because of the lack of exposed crystalline rocks over most of North Greenland it is uncertain whether the rocks of Victoria Fjord form the extension of the Archaean basement beneath the Rinkian and Caledonian fold belts, or whether they are separated from these by an area of Proterozoic crust.

References

Hansen, B. T., Higgins, A. K. & Borchardt, B. in press: Archaean U-Pb zircon ages from the Scoresby Sund region, East Greenland. *Rapp. Grønlands geol. Unders.*

Henriksen, N. & Jepsen, H. F. 1985: Precambrian crystalline basement at the head of Victoria Fjord, North Greenland. *Rapp. Grønlands geol. Unders.* **126,** 11–16.

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

Kalsbeek, F. 1986: The tectonic framework of the Precambrian shield of Greenland. A review of new isotopic evidence. *Rapp. Grønlands geol. Unders.* **128,** 55–64.

Kalsbeek, F. & Jepsen, H. F. 1980: Preliminary Rb-Sr isotope evidence on the age and metamorphic history of the North Greenland crystalline basement. *Rapp. Grønlands geol. Unders.* **99,** 107–110.

Kalsbeek, F. & Pidgeon, R. T. 1980: The geological significance of Rb-Sr whole-rock isochrons of polymetamorphic Archaean gneisses, Fiskenæsset area, southern West Greenland. *Earth planet. Sci. Lett.* **50,** 225–237.

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. *Can. J. Earth Sci.* **21,** 1126–1131.

Krogh, T. E. 1973: A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations. *Geochim. cosmochim. Acta* **37,** 485–494.

McIntyre, G. A., Brooks, C., Compston, W. & Turek, A. 1966: The statistical assessment of Rb-Sr isochrons. *J. geophys. Res.* **71,** 5459–5468.

Pedersen, S. A. S. & Holm, P. M. 1983: The significance of a Middle Devonian K/Ar age of an intrusive rock in the southern part of the North Greenland fold belt. *Bull. geol. Soc. Denmark* **31,** 121–127.

Persson, P.-O., Wahlgren, C.-H. & Hansen, B. T. 1983: U-Pb ages of Proterozoic metaplutonics in the gneiss complex of southern Värmland, south-western Sweden. *Geol. Fören. Stockholm Förh.* **105,** 1–8.

Stacey, J. S. & Kramers, J. D. 1975: Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth planet. Sci. Lett.* **26,** 207–221.

Steiger, R. H. & Jäger, E. 1977: Subcommission on Geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth planet. Sci. Lett.* **36,** 359–362.

Steiger, R. H., Harnik-Šoptrajanova, G., Zimmermann, E. & Henriksen, N. 1976: Isotopic age and metamorphic history of the banded gneiss at Danmarkshavn, East Greenland. *Contr. Miner. Petrol.* **57,** 1–24.

York, D. 1969: Least squares fitting of a straight line with correlated errors. *Earth planet. Sci. Lett.* **5,** 320–324.