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K/Ar dateringer af det prækambriske
grundfjeld i Danmark

I kommission hos
C. A. REITZELS FORLAG
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CONTENTS

ABSTRACT

K/Ar age determinations on granites and pegmatite from the island of Bornholm give results between 1255 and 1340 m.y. Ages between 1300 and 1500 m.y. are common in Scandinavia, Russia and North America. They are believed to represent a period of anorogenic plutonic activity.

K/Ar age determinations on core samples from deep tests made in Jutland and on Fyn give acceptable results between 800 and 900 m.y. for the crystalline basement. This indicates a relation to the 900–1200 m.y. orogenic episode recorded in Southern Norway and in Central Europe.

INTRODUCTION

Three years ago the analytical methods applied in the Copenhagen geochronological laboratory were described in a Danish scientific journal (Larsen & Møller, 1968a). New instruments and new techniques have since then been taken into use for the determination of argon and potassium. The analytical techniques applied at the present time are reported in the first part of this paper.

Part two contains a presentation of the first results of K/Ar age determinations on crystalline basement rocks exposed on Bornholm, a Danish island of 587 km^2 situated in the Baltic Sea south of Sweden. The samples were collected in part by Mr. T. Jørgart and Mr. O. Jørgensen, and in part by the author himself.

The six age determinations from Bornholm taken alone are difficult to evaluate, so the author has chosen to draw attention to the regional distribution of ages similar to those observed on Bornholm.

Part three of this paper is a report of three age determinations made on drill core samples from deep tests in Jutland and on Fyn. These tests were made by the Danish American Prospecting Company, which up to 1957 was financed by Gulf Refining Company, later by Standard Oil of New Jersey. The core sections were kindly put at my disposal by Dr. L. Banke Rasmussen of the Danish Geological Survey.

ACKNOWLEDGEMENTS

The author would like to thank dr. A. Noe-Nygaard, dr. H. Micheelsen and dr. C. K. Brooks for their kind advice during the preparation of the manuscript.

PART I: ANALYTICAL TECHNIQUES

DETERMINATION OF POTASSIUM

A Perkin-Elmer model 303 atomic absorption spectrophotometer was used for the determination of potassium.

The introduction of atomic absorption to isotopic dating is of fairly recent date (GAMOT et. al., 1970). Very little has otherwise appeared in litterature about the determination of potassium in micas and hornblendes by atomic absorbtion. Several problems appeared in the course of establishing a routine procedure for potassium analysis.

The use of HF + H_2SO_4 for bringing silicate samples into solution (TRENT and SLAVIN, 1964) cannot be recommended. Precipitated sulphates of certain elements are quite difficult to redissolve. Furthermore high concentrations of the sulphate ion seem to cause interferences in the determination of potassium by atomic absorption (ALTHAUS, 1966).

Perchloric acid is widely used together with HF for decomposing silicate samples (BELT, 1967). When this method was used on micas it was often difficult to obtain a clear solution free of precipitates. For these minerals better results were obtained using the pure HF decomposition technique described by LANGMYHR & PAUS (1968). Clear solutions were generally obtained on samples of biotite and muscovite and on whole rock samples, whereas hornblendes gave rise to precipitates, which were difficult to dissolve after addition of boric acid solution. Accordingly the precision obtained on hornblende is somewhat poorer than the precision determined from analyses on micas.

Details of the hydrofluoric acid decomposition method as employed in this laboratory are described in the following:

The samples are decomposed in 50 or 125 ml polypropylene Erlenmeyer flasks of heavy quality (Plastibrand – Nalgene) using 5 ml of HF. In order to avoid loss of HF the flasks are covered with a teflon disc, which again is kept in place by a piece of thin plastic foil.

The flask is heated on a sand bath to 100–110°C for 30 minutes. The boiling point of the azeotropic mixture of HF and H_2O (38,26 % HF) is 112°C. After cooling, 30 ml of saturated boric acid solution is added, and the flask is heated another 30 minutes on a water bath using a magnetic stirrer. After removing the stirring magnet, the solution is diluted to 50 or 100 ml. This concentrated sample solution normally remains clear and can be stored in polythene bottles.

The final dilution to potassium concentrations of 1–5 ppm should take place shortly before the absorption measurement in order to reduce the effect of ion exchange between diluted sample solution and the walls of the polythene bottle. Such exchange effects seem to be the main cause of erratic results. Pyrex should be used for the potassium standards, where no HF is present. According to BERNAS (1968) the fluoboric acid HBF_4 should hydrolyze so slowly, that pyrex glassware may be used safely for a period of up to two hours. In our experience even short exposures to pyrex may cause serious potassium contamination. Bottles for diluted samples should be either kept and cleaned seperately or even better used only once.

Table 1
Potassium analyses on international standards

		Percentage K_2O			
Standard	issued by	measured values	mean value	mean of published values	References
AGV-1 andesite	U.S. Geol. Survey	2.81 2.89 2.91 2.93	2.89	2.89$_8$	FLANAGAN (1969, p. 109)
BCR-1 basalt	U.S. Geol. Survey	1.62 1.67 1.69 1.69	1.67	1.68$_4$	FLANAGAN (1969, p. 109)
Bern 4M muscovite	Miner.-Petr. Inst. univ. Berne.	10.1 10.1 10.3 10.4.	10.2	10.45	Mean of 21 determinations from 13 different laboratories collected for the Colloquium on the Geochronology of Phanerozoic Orogenic Belts, Zürich-Berne, 1969.

In order to suppress interference due to varying amounts of other alkalies a solution of CsCl in hydrochloric acid is added. The diluted sample solution contains 0,1 % Cs_2O and about 4 % HCl. The same amounts of Cs_2O and HCl are added to the standards.

The absorption is measured at 766.5 nm or 769.9 nm wavelength. The first line is more sensitive than the second and is thus most commonly used. It is sufficiently linear up to 5 ppm K_2O. If the diluted sample should turn out to have a potassium content above 5 ppm the line 769.9 nm can be used, as it may be considered linear up to concentrations of 8–10 ppm.

An arc discharge lamp is used as light source. A recorder is used as output device. Digital readout equipment is not suitable for these measurements because the stability of the flame and nebulizer must be checked continuously.

The precision of the potassium determinations was calculated from potassium values obtained on 15 solutions of the same sample, each solution prepared seperately from dry rock powder. The coefficient of variation (the ratio of the standard deviation to the mean expressed in percent) determined from these measurements was 1.2 %.

Accuracy was evaluated by measurements on international standards: two whole rock standards issued by the U.S. Geological Survey and one muscovite standard circulated by the geochronological laboratory in Berne, Switzerland. The results are shown in table 1.

All K_2O values used in the age calculations are mean values of two or more independant determinations.

DETERMINATION OF RADIOGENIC ARGON

The radiogenic argon is determined by isotope dilution using an AEI MS 10 mass spectrometer. Calibrated amounts of ^{38}Ar are added from break seal tubes.

The vacuum system for sample melting and gas purification is shown in fig. 1. The samples are wrapped in molybdenum foil and placed in a molybdenum tube approximately 10 mm in diameter. The tube is suspended inside an evacuated tube of clear quartz by means of a platinum wire. The molybdenum tube containing the sample is heated using a 10 kW high frequency induction generator. The gas is cleaned using liquid nitrogen traps, a copper oxide furnace and a titanium sponge getter. During the melting of the sample the argon is trapped continuously on charcoal cooled to the temperature of liquid nitrogen. ^{38}Ar spike is added to the system during the melting procedure. After the argon gas has been purified it is transferred to the mass spectrometer inlet system. From here the gas is introduced into the mass spectrometer through a Granville-Phillips variable leak valve. The mass spectrometer is pumped by means of an AEI 25 l/sec ion pump connected to the mass spectrometer through a bakeable high-vacuum valve. The mass spectrometer is run dynamically. Mass discrimination is checked every day by measurements on an argon standard. The ^{38}Ar spikes were calibrated against the same argon standard.

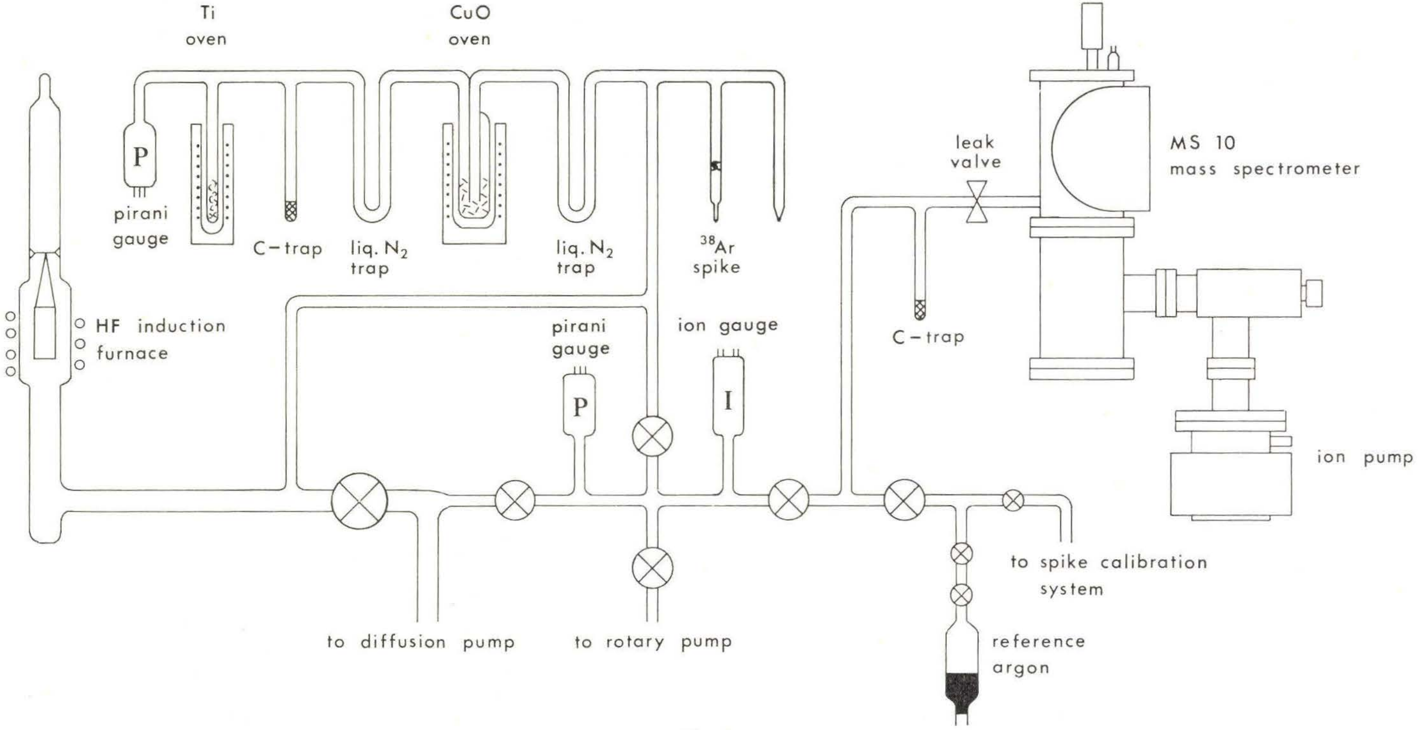
Ti
oven
CuO
oven
P
pirani
gauge
C-trap
liq. N_2
trap
liq. N_2
trap
^{38}Ar
spike
leak
valve
MS 10
mass spectrometer
HF induction
furnace
pirani
gauge
P
ion gauge
I
C-trap
ion pump
to spike calibration
system
to diffusion pump
to rotary pump
reference
argon

Fig. 1

PART II: THE CRYSTALLINE BASEMENT OF SOUTHEASTERN SCANDINAVIA

THE PRECAMBRIAN OF BORNHOLM

Review of earlier work

Geological investigations by USSING around the turn of the century resulted in a sketch map showing the areal distribution of the various granites of Bornholm (USSING, 1902). The units marked on USSINGs map are applied at this present day.

The geological map of Bornholm on the scale 1:100 000 was published by GRÖNWALL and MILTHERS in 1916, but this shows only details concerning the sedimentary cover.

CALLISEN (1934) made an extensive petrographical study of the granites, aplites, pegmatites and younger basic dykes on Bornholm. Her description includes a 1:100 000 map showing the distribution of the various granites. CALLISEN regarded all the granitic rocks as differentiates of a single magma. Adopting USSINGs units of classification she described Rønne granite, Vang granite and striated granite as early products of differentiation, while Hammer granite and Svaneke granite and associated aplites and pegmatites were considered to be late differentiates of that same magma.

While CALLISEN (1934) was studying the Precambrian basement from a petrographical point of view, German geologists from the university of Greifswald examined the structural features, (BUBNOFF, 1932, BUBNOFF & KAUFMANN, 1933, BUBNOFF, 1938, 1942). According to their view the striated granite was formed by the movement from north to south of a semi-plastic magma. Differentiation of this magma produced intermediate granites (Vang granite and Rønne granite) along the margins of the intrusion, while the central parts were altered to a more leucocratic granite examplified by the Almindinge granite on Central Bornholm. The Hammer granite was regarded as a magmatic unit formed at the same time as the main intrusion, while the Svaneke granite was accepted as a seperate intrusion genetically related to late flexural movements on Eastern Bornholm.

The interpretation of the Precambrian of Bornholm published by MICHEELSEN (1961a, 1961b) deviates significantly from the previous conceptions. The rocks on Bornholm are believed to be products of a metasomatic granitisation of granulite facies gneisses. The leucocratic Hammer granite and the aplites and pegmatites associated with this granite, are the extreme products of granitisation. The foliation prominent in the rocks of

Central Bornholm (in USSINGS and CALLISENS "striated granite") is considered to be a relict axial plane foliation. MICHEELSEN therefore used the term "gneiss" instead of "striated granite" to describe the rocks on Central Bornholm. The term "gneiss" is now in common use, although the term is actually more interpretive than descriptive.

Micheelsens interpretations were more or less accepted by NOE-NYGAARD (1963) as well as by SØRENSEN (1967) in their summaries of the Precambrian rocks of Bornholm.

During the last few years a number of senior students of the universities of Århus and Copenhagen have made detailed investigations on Bornholm. This group of younger geologists tend to oppose the metasomatic concept and regard the granites as anatectic granites formed at the expense of the Bornholm gneiss.

JØRGART (1968) has studied the Hallegård granite, a minor granitic mass occurring in the gneisses of Southeastern Bornholm. His investigations have shown that the Hallegård granite has been in a partly molten state, that the border between granite and gneiss marks the front of mobility, and that the amount of molten material decreases gradually as one moves from the contact into the surrounding gneiss. The magma probably formed by anatectic melting of the gneiss.

RØNSBO (pers. comm.) has studied the distribution of major and minor elements in the Hammer granite and in fine-grained leucocratic rocks, which occur as minor intrusive masses on Northern Bornholm. The chemistry of the Hammer granite shows strong evidence of magmatic differentiation. The fine-grained leucocratic rocks are interpreted as late magmatic differentiates.

PLATOU (1970) has investigated the Svaneke granite and its surrounding gneisses. He is able to divide the Svaneke granite into a number of specific subtypes differing from each other in composition and degree of mobility. Certain border types of Svaneke granite have been formed in situ by recrystallisation of the gneisses, while other types show evidence of a higher degree of mobility. Dykes of granite and pegmatite are found in the Svaneke granite, and they seem to be genetically related to the mobile phases of the granite.

Much work has been put into the study of the crystalline rocks of Bornholm in the recent years, but little has been added to our knowledge of the age relations between the different types of granite on Bornholm. Several authors have expressed the opinion that the Svaneke granite formed after the Hammer granitisation, and that the Rønne and Vang granites belong to a group of older granites, but the conclusive evidence for such a chronological order seems to be lacking. The gneiss apparently reached its present state before the formation of the anatectic granites, but we cannot say whether or not these events took place within a single period of orogenic activity.

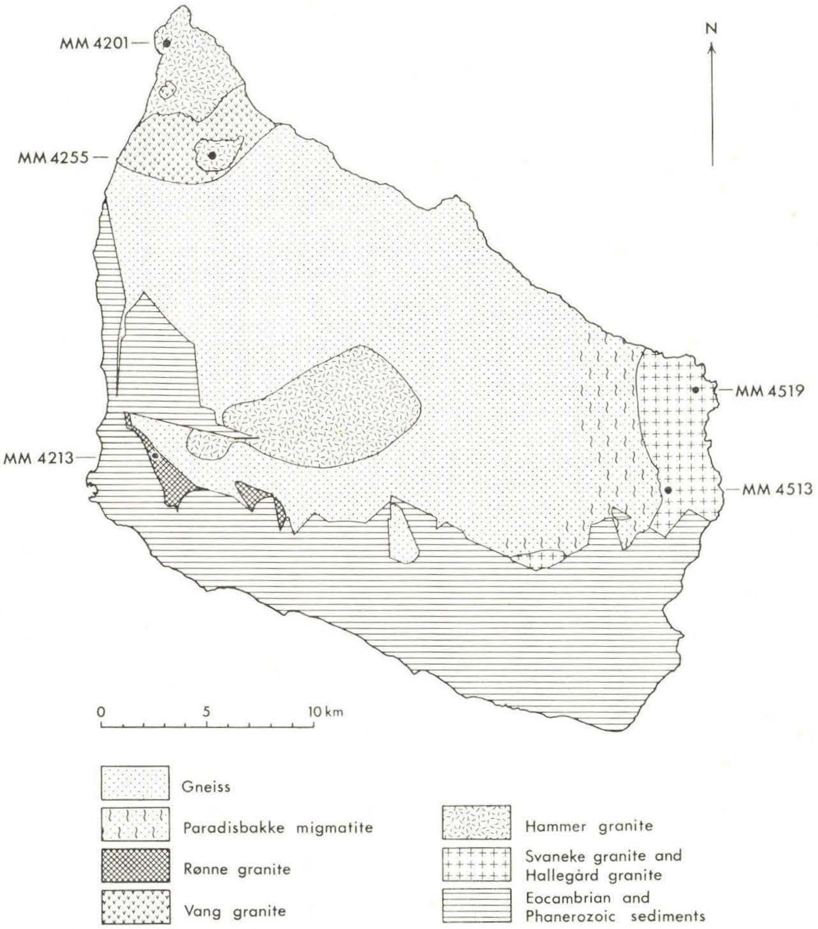

Fig. 2

K/Ar results from Bornholm

The results of six K/Ar age determinations are given in table 2 (sample description: Appendix B). The error limits assigned to the age values are estimates of the analytical precision (i.e. reproducibility) at the 1 σ confidence level. We have insufficient data to evaluate the accuracy of the argon measurements. As indicated by the data in table 1 the accuracy of the potassium determination is probably better than 2 % as far as biotites and muscovites are concerned.

Of the six age determinations four fall between 1320 and 1340 m.y. Two age values are low: The hornblende from sample MM4213 of Rønne granite and biotite from sample MM4519, Svaneke granite from Pærebakke quarry. The deviation of the hornblende age (1285 ± 15 m.y.) from the main group of biotite ages is hardly significant, as our method of potassium determination shows a fairly poor precision in the case of hornblende. The low age value for the Pærebakke biotite remains unexplained.

The K/Ar ages of the Bornholm granites are roughly concordant. The "coincidence" between biotite and hornblende ages shows that the rocks cooled fairly quickly. If the cooling had been slower one would expect the hornblende age to be significantly higher than the age of biotite, because on cooling hornblende becomes a closed system at a higher temperature than biotite.

The radiometric ages may be interpreted in 3 ways:

1) The Bornholm intrusive granites were all emplaced during a period of igneous activity around 1340–1400 m.y. At about 1340 m.y. the rocks had cooled to temperatures, at which argon loss by diffusion from biotite ceased.

2) The basement rocks of Bornholm are of different age. The gneisses and some of the granites were formed during the Svecofennian orogeny. Other granites (such as the Svaneke granite) belong to a later period of post-orogenic magmatic activity. During the latter period older rocks must have been subjected to temperatures that permitted complete argon loss from biotite and hornblende.

3) All the granitic rocks on Bornholm are of Svecofennian age. The K/Ar ages may reflect the time of uplift and cooling of the basement, but it seems more likely, that they were caused by a rise in temperature during a period of post-Svecofennian magmatic activity of which no obvious traces have yet been recorded on Bornholm.

Rb/Sr age work will probably demonstrate, which of these three possibilities is correct.

Recent Rb/Sr age determinations on rocks from Southern Norway and Sweden have shown that plutonic rocks were formed in Southern Scandinavia after the end of the Svecofennian orogenic episode. These results will be discussed later in this paper.

PRECAMBRIAN CHRONOLOGY OF SOUTHEASTERN SWEDEN

Already in 1891 Cohen and Deecke pointed out the similarities between the granites of Bornholm and the basement rocks of Blekinge (Southeastern Sweden). They compared the Svaneke granite with the Karlshamn granite of Blekinge, and they correlated certain gneisses in Blekinge with the striated granite (gneiss) of Bornholm.

In 1936 Norin published a detailed petrographic description of the rocks of Western Blekinge, and he presented also a geological sketch map of that region. His mapping was later extended into the adjoining parts of Skåne and Småland (Norin, 1959).

Table 2

K/Ar age determinations from Bornholm

Sample No.	Rock type	Quarry	Mineral	K_2O pct.	$\frac{^{40}Ar_R}{^{40}K}$	Age m. y.
MM 4255	Pegmatite	Borreløkken	Biotite	7.84	0.1121	1320 ± 40
MM 4213	Rønne granite	Klippegård	Hornblende	1.02	0.1079	1285 ± 15
MM 4213	Rønne granite	Klippegård	Biotite	6.32	0.1131	1330 ± 15
MM 4519	Svaneke granite	Pærebakke	Biotite	7.81	0.1041	1255 ± 15
MM 4513	Svaneke granite	Helletsgård	Biotite	7.05	0.1127	1325 ± 15
MM 4201	Hammer granite	Hammeren	Biotite	7.4	0.1147	1340 ± 30

$\lambda_e = 5{,}85 \times 10^{\div 11}\ y^{\div 1}$; $\lambda_\beta = 4{,}72 \times 10^{\div 10}\ y^{\div 1}$; $^{40}K/K = 1{,}19 \times 10^{\div 4}$

A tectonic study of parts of Blekinge, and the Karlshamn granite in particular, was made by HABETHA (1936). He further ventured a detailed comparison, structurally and chemically, between the rocks of Blekinge and the granites of Bornholm.

According to NORIN the granites of Blekinge may be devided into an older group (gneiss-granite in Western Blekinge and Tving granite east of the Karlshamn massif) and a younger group comprising fine-grained granite of Halen-Spinkamåla type and coarse-grained granite of Karlshamn type. The granites cut and migmatise a series of supracrustal rocks, the Västanå series. The lowermost unit of this series is a sequence of altered volcanics of rhyolitic composition ("hälleflinta"). The hälleflinta grade into fine- to medium-grained gneisses, Blekinge coastal gneiss. In Småland north of Blekinge the Precambrian basement consists mainly of acid volcanic rocks, the Småland porphyries, and granites, the so-called Växjö granites. Associated with these rocks are also gabbros and norites. The red Växjö granite is of granitic composition often developed with large "augen" of potash feldspar. Grey Växjö granites are tonalitic to granodioritic in composition. NORIN (1959) correlates the grey Växjö granite with the older group of granites in Blekinge (gneiss-granite and Tving granite). These granites are considered to be late-kinematic granites belonging to an early orogenic episode during which supracrustal rocks in Blekinge were deformed and gneissified. NORIN refers the Halen-Spinkamåla granites to a younger orogenic episode and consideres the coarse-grained granites of Karlshamn type to the post-kinematic granites related to this second episode. The Småland porphyris and the red Växjö granites are younger than the granites of the first episode but apparently predate the young granites in Blekinge. In the terminology of MAGNUSSON (1936) the granites of Southeastern Sweden may be referred in part to the Svionian Cycle (NORIN's first orogeny) and in part to the Gothian Cycle (NORIN's second orogeny).

K/Ar age determinations by GERLING and coworkers in Leningrad seemed to favor MAGNUSSONS concept of two independant orogenic cycles (MAGNUSSON, 1960). K/Ar ages below 1700 m.y. are common in Southeastern Sweden while gneisses and granites in Central and Northern Sweden yield dates generally between 1700 and 1850 m.y.

Since MAGNUSSON published his interpretations in 1960 a number of Swedish rocks have been dated at the geochronological laboratory in Stockholm. Rb/Sr isochron work has shown that supracrustal rocks, formerly referred to the Gothian Cycle, are in fact Svecofennian. Växjö granite in the Stralsnäs area east of lake Vättern is 1740 m.y. old (WELIN et al., 1966). Pegmatites and aplites in the Västervik area give a similar age, when dated by the U/Pb method (WELIN & BLOMQVIST, 1966). The result of this work must be that "... the Gothian Cycle must be disregarded, which conclusion is stated by the fact that there is no definite indication that the

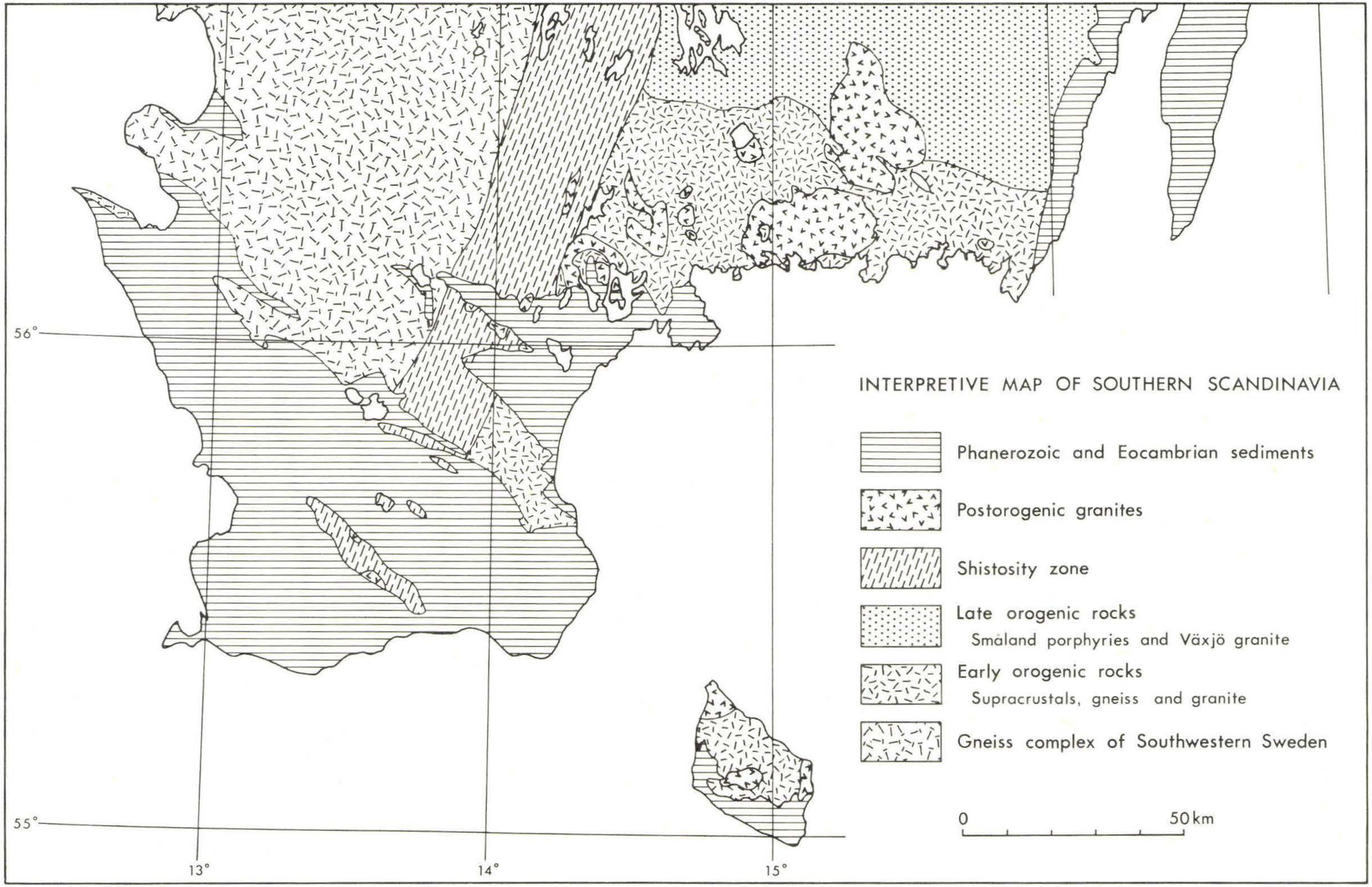
INTERPRETIVE MAP OF SOUTHERN SCANDINAVIA
Phanerozoic and Eocambrian sediments
Postorogenic granites
Shistosity zone
Late orogenic rocks
Småland porphyries and Växjö granite
Early orogenic rocks
Supracrustals, gneiss and granite
Gneiss complex of Southwestern Sweden
0
50 km
56°
55°
13°
14°
15°

Fig. 3

supracrustal rocks in southeastern Sweden are younger than the Svecofennian sediments and volcanics" (Welin, 1966).

Lundegaardh et. al. (1967) attempted to preserve the term "Gothian" in the concept of a Gothian Era. This was understood as the period of geological time during which the post-Svecofennian volcanics and plutonic rocks were emplaced.

Welin (1966) preferred to abandon the term "Gothian" altogether. Welin recognised a period of anorogenic plutonic activity separating two periods of orogenic activity, the Svecofennian period and the Dalslandian (or Sveconorwegian) period.

The K/Ar values published by Magnusson (1960) may be interpreted in the light of our present understanding of the chronology of the Swedish Precambrian[1]:

The K/Ar ages in Southeastern Sweden ranging from 1650 m.y. to 1380 m.y. may reflect the time of cooling following a post-Svecofennian plutonic episode. The lowest age (1380 m.y.) was obtained on the Karlshamn granite, which is believed to be one of the youngest granites in Southeastern Sweden.

Rocks occurring in the vicinity of the "schistosity zone" of Southern Sweden give still younger K/Ar ages in the range 1200–1300 m.y. (Vaggaryd syenite: 1235 m.y.). These ages may, however, be low due to the influence of the Dalslandian episode, which has overprinted all rocks west of the schistosity zone with ages of 900–1100 m.y. Priem et al. (1968) suggest an age of 1550 ± 100 m.y. for hyperite dolerite dykes in the schistosity zone. On Romeleåsen in Skåne gneisses in the schistosity zone are cut by a granite, the Romele granite. Welin & Blomqvist (1966) analysed monazite from an aplite vein associated with the Romele granite together with minerals from pegmatites related to the Karlshamn granite. These samples together define an isochron of 1455 m.y. in the $^{206}Pb/^{238}U - ^{207}Pb/^{235}U$ concordia diagram. At the present time this is probably the best estimate of the ages of the Karlshamn and Romele granites.

RADIOMETRIC AGE DETERMINATIONS ON POST-OROGENIC ROCKS IN EUROPE, GREENLAND AND NORTH AMERICA

Scandinavia

The sub-Jotnian volcanics (Dala-porphyries) in Central Sweden have been dated by the Rb/Sr isochron method. The original age determination re-

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[1] The decay constants used by the Russian geochronologists in 1960 were $\lambda_e = 5.50 \times 10^{-11}$, $\lambda\beta = 4.72 \times 10^{-10}$ and $^{40}K/K = 1.22 \times 10^{-4}$ (Gerling & Polkanov, 1958; Zhirov et al., 1961 p. 285). Before comparing the early Russian age values with the K/Ar dates reported in the present paper the corrections given in appendix C should be applied.

ported by Welin et al. (1966) giving 1685 m.y. has been reexamined. A revised age of 1669 ± 35 m.y. was recently issued by Welin & Lundqvist (1970). Dutch geochronologists in Amsterdam have dated similar volcanics and their associated granites in the Trysil area in Norway. Their data from Trysil indicate an age of 1590 ± 65 m.y.[1] (Priem et al., 1970).

Rb/Sr determinations of granite-gneiss of the Tinnsjö region in Southern Norway define a preliminary isochron of 1358 m.y. (Verschure et al., 1970)

Charnockitic-granitic migmatites in Rogaland, Southwestern Norway, have also been dated by the Rb/Sr whole rock method (Versteeve, 1970). The best isochron fit corresponds to an age of 1478 ± 78 m.y. The dated rocks are interpreted as belonging to a series of granitic bodies deformed and recrystallised under high-grade metamorphic conditions during the Dalslandian (Sveco-norwegian) orogenic episode.

Zircons from the "intrusive" anorthositic complex of Central Rogaland and its surrounding are all 1000–1050 m.y. old according to U/Pb determinations by Michot and Pasteels (1968, 1969).

Finland

Post-Svecofennian plutonic rocks in Finland comprise the rapakivi granites, their associated gabbros and anorthosites, and a number of anorogenic granites apparently coeval with the rapakivi granites.

U/Pb measurements on zircon from 6 different post-orogenic granites in Finland have yielded ages between 1630 and 1675 m.y., while Rb/Sr and K/Ar determinations on three of these granites gave slightly lower ages ranging down to 1550 m.y. (Kuovo, 1958).

The Jotnian sediments have been dated in Leningrad by the K/Ar method (reported by Simonen 1960). The Muhos shales gave ages of 1280 and 1310 m.y., while an age of 1300 m.y. was obtained for red shale in the Satakunta region.

Eastern Europe

Precambrian rocks are exposed in Ukraine. In Buelorussia and in Northeastern Poland the cover of Phanerozoic rocks is fairly thin and Precambrian rocks have been reached in a great number of bore holes. A large number of K/Ar age determinations on drill core samples give results between 1150 and 1500 m.y. Some Russian geologists (Semenenco 1967, Semenenco et al. 1968) accept this as evidence for a large orogenic belt stretching from Sweden through Poland (Przewlocki et al. 1962) eastwards to the chain of the Ural mountains. This is recognised as the belt of Gothian-Ovruch folding.

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1) Different ^{87}Rb decay constants were used: Welin: $1.39 \times 10^{\div 11}$ y $^{\div 1}$;
Priem: $1.47 \times 10^{\div 11}$ y$^{\div 1}$

On a tectonic sketch map of the Russian platform BOGDANOV (1965) has marked linear structural features in the Precambrian basement as deduced from magnetic anomalies. These linear features generally trend N-S to NW-SE. No structural features support the idea of an orogenic belt trending E-W.

Other Russian geologists oppose to SEMENENCO's interpretation. They believe that the age results mentioned above are evidence for a long period of postorogenic, magmatic activity following the Svecofennian-Karelian orogeny. VINOGRADOV & TUGARINOV (1961) concluded: "While the formation of the Ukrainian and Baltic shields ended approximately about 1900 to 1700 m.y. ago, the magmatic activity on the territory of the Russian platform continued until 1000 m.y. ago".

Greenland

Unpublished K/Ar age determinations made recently in this laboratory demonstrate that the Ketilidian metamorphism in South Greenland is at least 1800 m.y. old. Late-kinematic and post-kinematic granites are abundant in South Greenland from the region around Julianehaab to Kap Farvel. The plutonism ended with the emplacement of basic to intermediate magmatic rocks of appinitic affinities mainly in the area northeast of Julianehaab (WALTON, 1965) and of alkaline granites partly of rapakivi type occurring between Julianehaab and Kap Farvel (BRIDGWATER, 1963). K/Ar and Rb/Sr mineral dating (BRIDGWATER, 1965, LARSEN & MØLLER, 1968b) has given cooling ages ranging from 1645 to 1500 m.y. for the late- to post-kinematic igneous rocks in South Greenland.

In the "Gardar"period plutonic activity commenced again in South Greenland. A lamprophyre dyke believed to have intruded quite early in the Gardar period has given an age of 1275 m.y. (LARSEN & MØLLER, 1968). Determinations on other early Gardar rocks, notably the Gardar dolerites, have generally given lower ages probably due to the effect of late-Gardar plutonism between 1000 and 1200 m.y.

North America

The chronology of the rocks exposed along the seaboard of Labrador between Hopedale and Hamilton Inlet (KRANCK 1953, GANDHI et al., 1969) is strikingly similar to the chronology now established in Southwest Greenland. The supracrustal rocks of the Aillik series in the Makkovik Bay area correspond to the Ketilidian sediments and volcanics, and post-kinematic granite (Strawberry granite) in that same area gives a K/Ar age of 1600 ± 34 m.y. in good agreement with similar plutonic rocks in the Julianehaab region. Post-kinematic intrusive bodies in the Makkovik Bay area ranging in composition from diorite to syenite also find their equivalents among the post-ketilidian plutonic rocks of Southwest Greenland.

Rocks of Paleohelikian age (STOCKWELL, 1964) are found in the Western Nain province of Labrador, where pyroxene granulites and anorthosites are interpreted as plutonic rocks intruded into a complex of older gneisses (Wheeler, 1955, 1960). According to K/Ar determinations these intrusives cooled between 1300 m.y. and 1500 m.y. (STOCKWELL in WANLESS et al., 1965). Similar deep-seated intrusions occurring within the belt of Grenville folding have recently proved to be of the same age as the rocks in the Western Nain province: Rb/Sr isochron work has given ages of 1336 ± 71 m.y. and 1465 ± 85 m.y. for pyroxene granulites in the Central Adirondacks, New York, and 1338 ± 47 m.y. for granulites at Westport, Ontario (SPOONER, 1969). Granites at Lake Muskoka and near North Bay, both in Ontario, yield Rb/Sr ages of 1500 ± 70 m.y. and 1330 ± 70 m.y. respectivily (DAVIS et al., 1967).

In the Front Range, Colorado, PETERMAN et al. (1968) have shown that the main period of deformation and metamorphism 1700–1750 m.y. ago was followed by a period of batholith emplacement between 1390 and 1450 m.y. as examplified by the Silver Plume and Sherman granites.

CONCLUSIONS

It is suggested that orogenic tectonic activity in the Canadian-Fennosarmatian Shield ceased approximately 1600–1700 m.y. ago. Plutonic activity continued, however, yielding volcanic material on the surface and igneous intrusive rocks at depth.

A rise of the thermal front might in certain areas have reset the mineral clocks without leaving any obvious trace of the thermal activity at the present level of erosion (interpretation 3, p. 13.). If this had been the case on Bornholm, one would expect a wider spread of age values. It has been demonstrated above that Svecofennian rocks in Southern Sweden show a wide spread in age values.

Post-Svecofennian granites are known to occur in Blekinge in Southern Sweden, and K/Ar ages there range down to 1380 m.y. when recalculated in accordance with the presently used decay constants. The difference in age values between the Karlshamn granite and the granites on Bornholm should therefore not stand in the way of a correlation between these rocks. In the oppinion of the author some of the Bornholm granites have formed during a period of post-Svecofennian plutonism. If this is true the K/Ar ages indicate the time of regional cooling following this plutonic episode (interpretation 2, p. 13.).

PART III: THE CRYSTALLINE BASEMENT OF SOUTHWESTERN SCANDINAVIA

EVIDENCE FROM DEEP TESTS IN DENMARK

Basement rocks have been reached in Northern Jutland (Frederikshavn: 1286 m), in Central Jutland (Grindsted: 1599 m, Arnum: 1814 m) and on Fyn (Glamsbjerg: 903 m). The rocks have been described by NOE-NYGAARD (1963). In all four deep tests the crystalline rocks are overlain by Permian or Mesozoic sediments. Older Palaeozoic deposits are lacking. There is therefore no stratigraphic evidence to prove a Precambrian age for the crystalline basement.

Early Palaeozoic rocks have been found, however, at a depth of 2542 m in the boring at Slagelse on Sealand. The drill penetrated 389 m of unmetamorphosed sediments of Cambrian to Silurian age (SORGENFREI & BUCH, 1964; POULSEN, 1969). Cambrian shales at Slagelse dip approximately 20° (strike unknown).

At Hønning just south of Arnum in Western Jutland horizontal sediments of Lower Permian age cover a series of grey to reddish shales of unknown age with a dip of about 37° (SORGENFREI & BUCH, 1964).

Although the Palaeozoic strata are strongly tilted by tectonic movements, they show no signs of regional metamorphism. Denmark has probably been subjected to germanotype movements being located as a forland area in relation to the Central European belts of Palaeozoic folding.

THE EXTENT OF PALAEOZOIC DEFORMATION IN NORTHERN EUROPE

The position of the northern boundary of Variscan folding along a line approximately E-W across Northern Europe at the latitude of Berlin seems to be generally accepted (GAERTNER, 1960; KÖLBEL, 1963).

The northern boundary of Caledonian folding is apparently still a matter of debate:

GAERTNER (1960) suggested that either the limit of Caledonian folding was located in Northern Europe slightly north of the limit of Variscan deformation and approximately parallel to the latter, or it crossed over Denmark joining up to the Caledonian front in Southern Norway. The first alternative, a Caledonian front slightly north of the Variscan front, was more or less agreed upon by KÖLBEL (1963), who however, on the basis of evidence

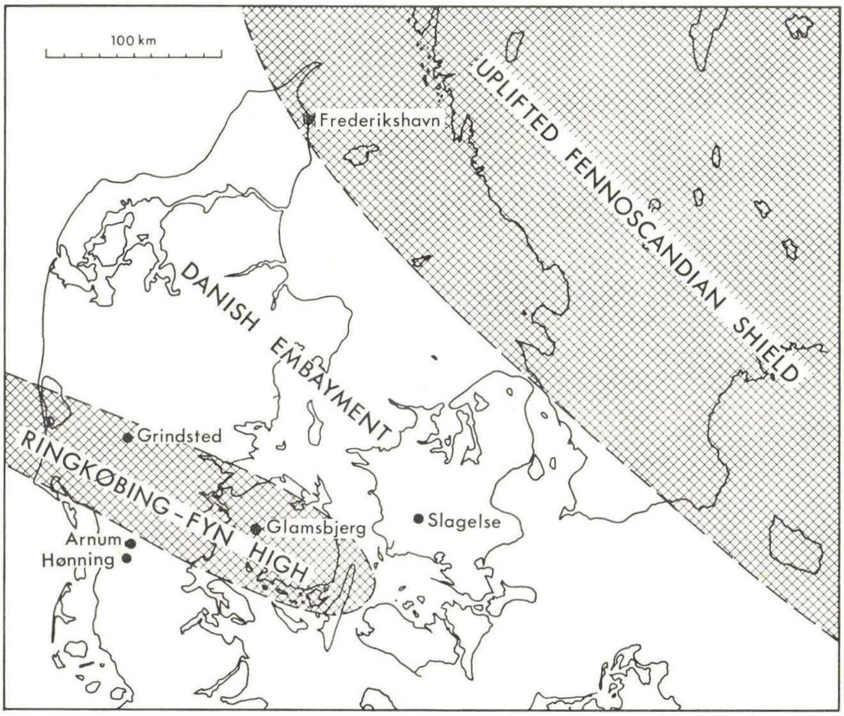

Fig. 4

Table 3
K/Ar age determinations from deep tests in Jutland and on Fyn

Sample No.	Rock type	Bore hole	Mineral	K_2O pct.	$\frac{^{40}Ar_R}{^{40}K}$	Age m. y.
MM 4218	Hornblende gneiss	Glamsbjerg	Hornblende	1.34	0.0596	815 ± 15
MM 4219	Biotite gneiss	Grindsted	Biotite	9.14	0.0645	870 ± 15
MM 4244	Biotite gneiss	Arnum	Biotite	4.45	0.0487	690 ± 15

$\lambda_e = 5.85 \times 10^{\div 11} y^{\div 1}$; $\lambda_\beta = 4.72 \times 10^{\div 10} y^{\div 1}$; $^{40}K/K = 1.19 \times 10^{\div 4}$

from borings on the island of Rügen off the coast of North Germany, moved the Caledonian front northwards forming a lobe into the Baltic Sea.

Franke (1967) argues that the inclination of the Palaeozoic strata observed on Rügen is the result of germanotype movements of a stable forland, not of orogenic folding. According to Franke the areas of Caledonian consolidation observed in the Netherlands are cut off further east by the front of Variscan deformation.

AGE DETERMINATIONS

Three samples were selected for radiometric dating, see appendix B. Of these samples two come from solid basement while the third, from Arnum, is a fragment of a boulder from a fanglomerate consisting of large angular rocks embedded in a hematite-carbonate impregnated sandstone. Judging from the shape of the rocks in the fanglomerate the distance of transport must have been quite limited.

The results of the three K/Ar age determinations are given in table 3. The samples of solid basement gneiss from Glamsbjerg and Grindsted give ages of 815 m.y. and 870 m.y. respectively. These results agree with K/Ar dates obtained in Southern Norway and Western Sweden (BROCH, 1964; MAGNUSSON, 1960).

The age of the biotite from Arnum, 690 m.y. is considerably lower than the ages of the other two samples. The potassium content of the Arnum biotite is low (4.45 % K_2O) in agreement with the X-ray diffraction determination of chlorite, which indicates about 55 % chlorite in the biotite (see table 4). In thin section chlorite may be identified as thin layers in the biotite grains. The chloritisation of the biotite probably occurred during diagenesis through the action of Mg- and Ca-rich solutions circulating in the sandstone matrix of the fanglomerate.

KULP and ENGELS (1963) report that in laboratory experiments alteration of biotite to chlorite at low temperatures by the proces of "base exchange" does not produce any significant decrease in the K/Ar age before the biotite lattice breaks down at 85–90 % Ar-loss. Only two years earlier the same laboratory reported preferential argon loss in leaching experiments (KULP & BASSETT, 1961).

In the case of the Arnum sample it is clear that the biotite-chlorite grains have lost argon in excess of potassium. Whether this argon loss was the immediate result of chloritisation or it is the result of continuous diffusion from biotite-chlorite composite grains cannot be decided. To my knowledge no experimental work has been done on determining the diffusion parameters of argon in interlayered biotite and chlorite.

THE DALSLANDIAN CYCLE

O'NIONS et al. (1969) report that biotites in the Bamble area of South Norway range from 1038 m.y. to 860 m.y. while hornblendes range between 1114 m.y. and 970 m.y. These authors place the thermal maximum of the Dalslandian metamorphic event at about 1110 m.y. and ascribe the spread of the K/Ar ages to slow uplift and cooling. They further remark that postkinematic granites elsewhere in South Norway are probably as young as 860 m.y.

Russian K/Ar age determinations on samples from Southwestern Sweden were reported by MAGNUSSON (1960). With the presently used decay constants these age values range from 1100 m.y. to 890 m.y. which is the age obtained on the post-kinematic Bohus granite.

The Precambrian basement of Denmark was certainly influenced by the Dalslandian episode, but it is impossible at the present time to say whether or not the amphibolite facies metamorphism observed in the basement rocks is related to the Dalslandian Cycle. The K/Ar ages might only reflect a Dalslandian thermal overprinting on older rocks as is believed to be the case in parts of Southwestern Sweden.

Recent age determinations on samples from Brittany (LEUTWEIN, 1968a, 1968b) have shown that the pre-Briovérien deformation observed in the metamorphics and igneous rocks of the Pentévrien took place about 900–1000 m.y. ago. Leutwein correlates this episode in Western Europe with the metamorphism in Bohemia by which the Moldanubian gneisses were formed, (ZOUBEK, 1965). In both regions the high-grade metamorphic rocks are discordantly overlain by a sequence of late-Precambrian rocks. The Dalslandian (Sveconorwegian) orogeny is therefore not limited to Scandinavia, but apparently extends over large parts of Central Europe.

APPENDIX A

CHLORITE IN BORNHOLM BIOTITES

The potassium content of a normal well-crystallised biotite is about 9 % K_2O. The potassium values for the dated samples from Bornholm (table 2) are all significantly low. This was quite unexpected, because all the samples appear unaltered in thin section, and only very little chlorite was seen in the biotites (see sample description in appendix B). In Rønne granite chlorite could not be found at all. Chlorite is present in biotites of Hammer granite and Svaneke granite. It occurs as thin layers in the biotite oriented parallel to the basal cleavage plane of the host mineral. In both Hammer granite and Svaneke granite the amount of chlorite seen in thin section seems to be at least an order of magnitude less than the amount of biotite present.

The chlorite contents of the biotites were estimated using an X-ray diffraction technique devised by R. J. Traill, Geological Survey of Canada, and reported by Rimsaite (1967). By measuring the intensity of the fourth basal reflection of chlorite and comparing it with the intensity of the third basal reflection of biotite it is possible to estimate in a semiquatitative way the ratio between chlorite and biotite in the sample:

$$\frac{\text{(Amount of chlorite)}}{\text{(Amount of biotite)}}\ \text{by weight} = \frac{I_{\mathrm{Chl}\ (004)}}{I_{\mathrm{Bi}\ (003)}} \times 4.5$$

The chlorite contents determined by this method are given in table 4. Biotites with above 10 % chlorite give chlorite contents, which are in good agreement with the potassium determinations, proving that chlorite contents may be seriously underestimated, when samples are examined in thin section. Biotites from pegmatite and Rønne granite give chlorite values, which do not agree with the potassium determinations possibly due to the limitations inherent in this method of chlorite determination.

All the biotites dated contain some chlorite. This may be a general feature for the granites of Bornholm. Callisen (1934) mentioned chlorite as an alteration product of biotite in Rønne granite (p. 35) and in Svaneke granite (p. 112), but did not comment on the occurrence of chlorite in Hammer granite.

Table 4

Determination of chlorite in biotite by X-ray diffraction

Sample No.	Rock type	Locality	$\frac{I_{Chl.\,(004)}}{I_{Bi.\,(003)}}$	Est. chlorite content %	K_2O content (%)	
					calc. from chlorite	atomic. absorpt.
MM 4255	Pegmatite	Bornholm	0.012	5.0	8.6	7.84
MM 4213	Rønne granite	Bornholm	0.068	6.3	8.4	6.32
MM 4519	Svaneke granite	Bornholm	0.158	13.6	7.8	7.81
MM 4513	Svaneke granite	Bornholm	0.288	22	7.0	7.05
MM 4201	Hammer granite	Bornholm	0.225	18	7.3	7.4
MM 4219	Biotite gneiss	Grindsted	0.000	0.0	9.0	9.14
MM 4244	Biotite gneiss	Arnum	0.26	55	4.1	4.45

APPENDIX B
SAMPLE DESCRIPTIONS

MM 4255:
Biotite from pegmatite, Borreløkken Quarry near Olsker, Bornholm.
14°47′E/55°14′N.

The pegmatite cuts an occurrence of Hammer granite, which at this locality is surrounded on all sides by granite of Vang type. The pegmatite is composed of red, perthitic microcline, white plagioclase, colourless quartz and large flakes of dark biotite. Graphic granite textures occur in parts of the pegmatite. Muscovite, fluorspar and gadolinite have also been found.

MM 4213:
Rønne granodiorite from Klippegård Quarry near Rønne, Bornholm.
14°45′E/55°06′N.

The dating sample of Rønne granodiorite corresponds closely to the description given by CALLISEN (1934). It is a dark grey, medium-grained rock composed mainly of plagioclase, microcline perthite, quartz, hornblende and biotite. The plagioclase grains have cores of saussurite. The microcline perthite is a string perthite occurring partly as single irregular grains approximately 0.5 mm in diameter, partly as overgrowths on plagioclase forming larger grains (1–3 mm), with a tendency towards a rectangular shape. The hornblende is pleochroic with colours between bluish green and olive green, and it displays a poikilitic texture typically embracing quartz, biotite and apatite. The biotite is green and has a refractive index for the Y/Z directions of about 1.65, 2V = 0–2°. The mica should thus correctly be termed lepidomelane as pointed out by CALLISEN (1934). In thin section the mica appears quite homogeneous, and chlorite could not be seen. Grains of opaque ore (dominantly ilmenite according to JENSEN, 1968) are surrounded by patches of sphene and often occur together with hornblende and biotite. Common accessories are apatite, sphene and zircon.

MM 4519:
Svaneke granite from Pærebakke Quarry near Svaneke, Bornholm.
15°08′E/55°08′N.

MM 4513:
Svaneke granite from Helletsgård, Helvedesbakker, Bornholm.
14°57′E/55°05′N

Both samples are of a coarse-grained red granite and display similar mineralogical features in thin section. The rock is composed of microcline perthite, plagioclase, quartz, biotite and hornblende. The microcline perthites occur as centimeter-size porphyroblasts, many of which include more or less resorbed grains of plagioclase and quartz. The perthite is partly a patch perthite, partly a string perthite. Some of the larger patches appear to be relict plagioclase inclusions rather than products of exolution. Plagioclase grains generally consist of a saussurite core surrounded by an unaltered rim of albite. Some plagioclases are completely intergrown with myrmekitic quartz, while other plagioclase grains carry no quartz at all. Biotites vary in colour between pale green (X) and dark green (Y/Z). A little chlorite is present in the biotite grains. Hornblende is strongly pleochroic with colours between light green and greenish blue. The mafic minerals commonly occur in patches together with opaque minerals, sphene, apatite, epidote and zircon. According to JENSEN (1968) magnetite is the dominant ore mineral in Svaneke granite.

MM 4201:
Hammer granite from Hammer Quarry, N. Bornholm.
14°46′E/55°16′N.

Medium-grained, reddish grey granite composed of microcline, quartz, plagioclase and biotite. Quartz grains are irregular in shape and are cut by numerous cracks. The perthite is a string perthite with intense patchwork twinning in the microcline component. Larger grains of microcline (3–5 mm) enclose plagioclase and rounded grains of quartz. Myrmekite, which is often seen in Hammer granite (CALLISEN, 1934) was not observed in this sample. The cores of the plagioclase grains are rich in sericite. Biotites whose colours range from pale olive green (X) to dark olive or brownish green (Y/Z) have been corroded and partially replaced by leucocratic minerals. A little chlorite is present in the biotite. Sphene is a common accessory. Ore minerals are not conspicuous, but some opaque material has formed as an alteration product of biotite.

MM 4218:
Hornblende gneiss, deep test at Glamsbjerg, Fyn.
10°08′E/55°18′N.
Core section at 909 m below rotary table at 71.3 m.

Medium-grained, dark green amphibolitic gneiss with semiconcordant veins of a rock somewhat lighter in appearance and probably of granodioritic composition. The core furthermore contains thin pegmatitic veins with large crystals of ore now altered to hematite. Anhydrite occurs as fissure filling material.

In thin section the amphibolitic gneiss chosen for dating is seen to be composed mainly of hornblende, plagioclase and quartz. The hornblende is green with a pale brown core. Other thin sections from nearby core sections contain microcline and green biotite. Sphene, apatite and zircon are common accessories. Chlorite, leucoxene and hematite are abundant as secondary alteration products.

MM 4219:
Biotite gneiss, deep test at Grindsted, Jutland.
8°50'E/55°45'N.
Basement gneiss: 1599–1647 m below rotary table at 34.9 m.

The gneiss is composed mainly of quartz, feldspar and biotite. In thin section only plagioclase was observed, but small amounts of microcline were found on inspecting the powdered sample. The biotite is strongly pleochroic: Pale green (X) to dark brownish green (Y/Z). Opaque iron ore is intergrown with biotite. Accessory minerals: Sphene, apatite and monazite. Chlorite in small amounts appears to be an alteration product of hornblende of which traces may still be found. Hematite is seen in minor amounts on cleavage surfaces in biotite.

MM 4244:
Biotite-hornblende gneiss from boulder in fanglomerate, deep test at Arnum, Jutland.
8°58'E/55°13'N.
Core section at 1833.4 m below rotary table at 42.7 m.

The sample is composed of quartz, feldspar and biotite. Plagioclases are easily identified by their polysynthetic albite twinning. No feldspars show the patchwork twinning characteristic of microcline. Most feldspars show signs of alteration along grain boundaries and cracks. The biotite is weakly pleochroic (X: pale green; Y/Z: variable between olive green and pale brown). Most biotite flakes are darkened due to exolution of hematite along cleavage planes. Carbonate material has crystallised along the cleavage planes of the mica books causing these to break apart in thin flakes. To a less extent carbonate has also been deposited elsewhere in cracks and along grain boundaries. Zircon is present.

A large number of thin sections of the Arnum core were available for study. In the upper part of the 30 m long core section of fanglomerate all the included rocks are quite heavily altered. The majority of the original minerals are replaced by carbonate and anhydrite. Hornblende has been replaced by chlorite, and micas are filled with hematite. Two sections of core appear to be less altered: A short section around 1833 m, from which the present dating sample was taken, and the final end of the Arnum core at 1844 m, where blocks of microcline-rich granitic rock appear in the core. This latter material has not yet been investigated.

APPENDIX C

CONVERSION TABLE FOR K/Ar AGES

Russian constants 1960 $\lambda_e = 5.50 \times 10^{\div 11}$ $\lambda_\beta = 4.72 \times 10^{\div 10}$ $K^{40}/K = 0{,}0122$ Age in m. y,	Constants used in this paper $\lambda_e = 5.85 \times 10^{\div 11}$ $\lambda_\beta = 4.72 \times 10^{\div 10}$ $K^{40}/K = 0{,}0119$ Age in m. y.	Difference in. m. y.
900	872	28
1000	970	30
1100	1068	32
1200	1166	34
1300	1264	36
1400	1362	38
1500	1460	40
1600	1557	43
1700	1655	45
1800	1753	47

DANSK SAMMENDRAG

K/Ar DATERINGER AF DET PRÆKAMBRISKE GRUNDFJELD I DANMARK

Ved dateringslaboratoriet i København er der nu udført 6 K/Ar-aldersbestemmelser på prøver fra det bornholmske grundfjeld og 3 dateringer af grundfjeldsprøver fra dybdeboringer i Jylland og på Fyn.

Resultaterne af aldersbestemmelserne på de bornholmske prøver ligger mellem 1255 millioner og 1340 millioner år. Fire af de seks resultater ligger over 1320 millioner år, og K/Ar-alderen af grundfjeldet anses for at være ca. 1340 millioner år. Dette resultat kan tolkes på flere måder:

1) De bornholmske graniter er alle dannet omkring 1340–1400 millioner inden for samme periode af magmatisk aktivitet. 1340 millioner er det tidspunkt, hvor bjergarterne var afkølet til så lav en temperatur (ca. 200°C) at tabet af argon ved diffusion fra biotit ophørte.

2) De bornholmske graniter er af forskellig alder. Gnejsen og muligvis også enkelte af de mere homogene granitiske bjergarter er dannet under den svecofenniske orogenese. Andre graniter (som f. eks. Svaneke-graniten) er dannet under en noget senere periode af magmatisk aktivitet, hvorunder de ældre bjergarter er blevet opvarmet til så høje temperaturer, at al tidligere dannet argon er tabt.

3) Alle Bornholms graniter er af svecofennisk alder. Den alder, K/Ar-dateringerne afspejler, kan være fremkommet ved, at området kun har hævet sig ganske langsomt efter den svecofenniske foldning, og at temperaturen derfor er forblevet høj gennem flere hundrede millioner år. Mere sandsynligt er det dog, at argontabet skyldes en yngre magmatisk aktivitet, som blot ikke har efterladt iøjnefaldende vidnesbyrd i de blottede dele af det bornholmske grundfjeld.

Den overvejende del af grundfjeldet i Småland og Blekinge har vist sig at være dannet i tilknytning til den svecofenniske foldning. U/Pb – og K/Ar-dateringer på bl. a. Karlhamngraniten i Blekinge kunne dog tyde på, at visse graniter i det sydligste Sverige er betydeligt yngre end det omgivende grundfjeld, – måske omkring 1400 millioner. Forfatteren hælder til den opfattelse, at de yngste graniter i Blekinge og enkelte graniter på Bornholm er dannet under en periode af magmatisk aktivitet omkring 1340–1500 millioner. K/Ar-aldre i dette interval er udbredt i Polen og Rusland såvel som i Skotland. Nye Rb/Sr dateringer på graniter i Sydnorge har givet ret pålidelige resultater omkring 1360 millioner år. De post-orogene graniter i Sydgrønland er en del ældre (min. ca. 1600 millioner), men i Nordamerika har man langs sydranden af det ældre prækambriske grundfjeldsområde adskillige intrusioner, hvis Rb/Sr-aldre ligger inden for det ovennævnte tidsinterval.

Aldersbestemmelserne på dybdeboringerne fra Jylland og Fyn giver resultater omkring 800–900 millioner år og bekræfter, at det danske grundfjeld er af prækambrisk alder. Lignende K/Ar aldre kendes fra Sydnorge, hvor betydelige dele af grundfjeldet er blevet omdannet under den dalslandiske orogenese. Det er sandsynligt, at grundfjeldet under det vestlige Danmark er dannet under denne foldning, som kan spores fra Norge ned til Mellemeuropa (Bretagne og Tjekkoslovakiet), men det kan ikke udelukkes, at dele af grundfjeldet i virkeligheden er betydelig ældre, – muligvis af svecofennisk alder.

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