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R. A. GAYER, D. G. GEE, W. B. HARLAND, J. A. MILLER,
H. R. SPALL, R. H. WALLIS, T. S. WINSNES

RADIOMETRIC AGE DETERMINATIONS ON ROCKS FROM SPITSBERGEN

NORSK POLARINSTITUTT
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DET KONGELIGE DEPARTEMENT FOR INDUSTRI OG HÅNDVERK

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ÅRBØKER

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Contents

Abstract

30 new radiometric age determinations of Spitsbergen rocks are detailed. Previously published data are listed for comparison giving a total of 76 determinations. The significance of these is discussed with the following general conclusions.

1. Late Pre-Cambrian metamorphism occurred in some areas affecting at least part of the Hecla Hoek succession; its stratigraphical relationship is not clear.
2. Intense and extensive Caledonian metamorphism and plutonism are reflected in apparent ages ranging from 450 to 360 million years (m. y.). The later events may overlap with possibly late Silurian, and Devonian sedimentation.
3. Some very localized intrusions with basic affinities give an apparent Carboniferous age.
4. Widespread basic intrusions generally evident as dolerite sills are of mid-Mesozoic age.

Introduction

Many geological problems in Spitsbergen invite investigation by radiometric age determination techniques, particularly by the K-Ar and Rb-Sr methods. With the development of these methods in Oxford and Cambridge, one of us (W. B. H.), having for some time directed an investigation of Spitsbergen from Cambridge, sought the collaboration of both L. R. WAGER and E. C. BULLARD to arrange the laboratory work. Facilities were readily made available, and another of us (J. A. M.) subsequently determined most of the rocks by the K-Ar method, while E. I. HAMILTON made some determinations by the Rb-Sr method. Collecting for this purpose on the Cambridge expeditions began in 1959 and continued as explained on pp. 6—7.

One of the first objects was to estimate the age of the metamorphism of rocks lying unconformably beneath fossiliferous Old Red Sandstone of Downtonian age. Some early results were published (HAMILTON, HARLAND and MILLER 1962). A related and outstanding problem in Spitsbergen geology has been the determination of the regional extent of this mid-Palaeozoic metamorphism, in relation to the possible occurrence of pre-Hecla Hoek ("Archaean") basement rocks in some parts of the area. With this in mind further collections in Vestspitsbergen were made by Cambridge expeditions, and some material from Nordaustlandet was provided by the Norsk Polarinstitutt.

In the meantime the first results from Nordaustlandet were published based on collections by earlier Oxford expeditions (HAMILTON and SANDFORD 1964) and other, more widely scattered, determinations from northern Spitsbergen were published by Russian workers from material collected by Leningrad expeditions

(KRASIL'SCHIKOV, KRYLOV and ALJAPYSHEV 1964). We are grateful to NATASCHA HEINTZ for translating this paper for our use. The availability of these two sets of new results decided us not to attempt to analyse material kindly loaned by WESTON BLAKE Jr. and TORE GJELSVIK who had collected it for other purposes.

In 1962 further Cambridge collections included material for a combined palaeomagnetic and age determination study of the Mesozoic basic sills.

All the data from material analysed in Cambridge are presented here. The determinations are only of igneous (intrusive) and metamorphic rocks. The essential data from the three publications already mentioned are tabulated, with the ages recalculated using the constants employed throughout this paper. For economy in this paper each determination listed is given a reference number which is used throughout.

Data

GEOGRAPHICAL DISTRIBUTION AND COLLECTION OF SAMPLES

The map (Fig. 1) shows the distribution of all the samples and their ages as listed in this paper (Tables I and II). The sequence of reference numbers in Table II gives the approximate order in which the laboratory determinations were made. The samples were collected on a series of expeditions and the following brief account is intended as an acknowledgement for this material.

Some specimens were taken from earlier collections, not made with isotope work in mind, as follows: (76) on the Cambridge Spitsbergen Expedition 1958 by M. D. FULLER (FRIEND 1959); (64) by J. L. CUTBILL, on the Cambridge Nordaustlandet Expedition 1958 (BATESON 1959); (48), (54) and (55) by T. S. W. on the Norsk Polarinstitutt expedition of 1957 (NORSK POLARINSTITUTT 1958); material (13—22) collected on Oxford expeditions to Nordaustlandet in 1924 (SANDFORD 1926), 1935—36 (SANDFORD 1950, 1956), and 1949 (SANDFORD 1950, 1954), were determined by the Rb-Sr method in Oxford (HAMILTON and SANDFORD 1964).

In 1959 (HARLAND 1960 a) specimens for isotope work were collected by the Cambridge expedition. The initial objects were to determine the ages of metamorphism of the Hecla Hoek (6—12), and of the intrusion of the post-metamorphic granites (1—5), (47), and from them to derive the maximum age for the base of the Old Red Sandstone in Spitsbergen (HAMILTON *et al.* 1962).

On excursion No. A 16 of the International Geological Congress 1960 (leaders; T. S. WINSNES, A. HEINTZ and N. HEINTZ (1960), and local leader K. BIRKENMAJER) W. B. H. collected samples of mica schist from the Isbjørnhamna formation (49), (50) from near the Polish I. G.Y. base hut in Hornsund.

In 1961 (HARLAND 1962) further collections bv R. A.G. and D. G. G. of metamorphic rocks in northern Haakon VII Land and Ny Friesland were made (51), (52), (59), (61), (69). In 1962 (HARLAND 1963) this programme was continued by R. A. G., D. G. G. and W. B. H. in Ny Friesland (56), (57), (58), northern Haakon VII Land (53), (60), (70—75), and in western Olav V Land (67), (68). At the same time Mesozoic dolerites were investigated by H. R.S. and collected in Bünsow Land (66), Dickson Land (62), (63), and Nordenskiöld Land (65). Collections made on subsequent expeditions have not yet been determined.

In 1962 and 1963 members of the Leningrad Expeditions of the Institute of the Geology of the Arctic collected from various parts of northern Spitsbergen (specimens 23—46), (KRASIL'SCHIKOV 1964, KRASIL'SCHIKOV *et al.* 1964).

PUBLISHED RADIOMETRIC DATA

The radiometric data, abstracted from HAMILTON *et al.* (1962), HAMILTON and SANDFORD (1964), KRASIL'SCHIKOV *et al.* (1964) are listed in Table I, so as to show (A) the reference number in this paper; (B) who collected the specimens; (C) who made the determination; (D) the field specimen number; (E) the locality; (F) the rock type; (G) the mineral determined; (H) the percentage of potash; (I) the volume of radiometric argon; (J) the rubidium content; (K) the total strontium content; (L) the strontium 87 content; (M) the apparent age in million years. The constants used for this are also given.

NEW RADIOMETRIC DATA

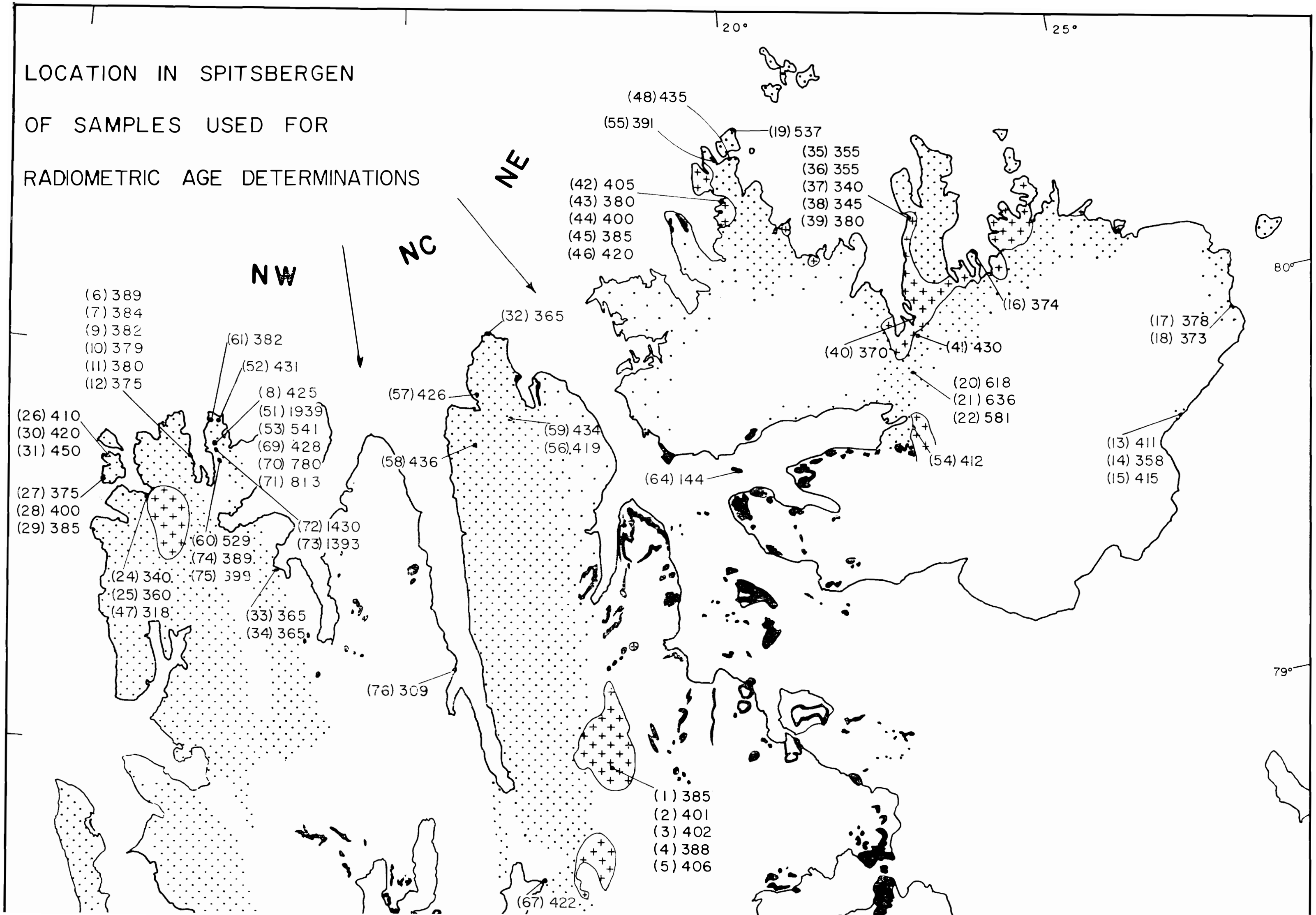
Unpublished data are listed in Table II with the same information where relevant as that in Table I.

PETROGRAPHIC AND STRUCTURAL DESCRIPTIONS OF SAMPLES

The following section contains brief petrographic descriptions of the 30 new samples used for the K-Ar determinations given in Table II, and also of the samples used for the K-Ar determinations given in HAMILTON *et al.* (1962) incorporated in Table I. The author of the petrographic comment is indicated by initials, and the descriptions have been edited by R. H. W. Those features particularly relevant to the radiometric values are stressed on p. 18 and p. 23. In each description the mineral determined is in *italics.*

To give more precise locations for these specimens, rectangular coordinates are given where available, at the end of each description, according to the official conformal cylindrical projection used by the Norsk Polarinstitutt, Oslo. (Origin of kilometre grid: East, parallel to and 100 km west of 15°E; North, 8500 km north of Equator).

(1), (2), (3), (4), (5). A coarse grained porphyritic granite. The phenocrysts consist of potash feldspar up to 3 cm in grain size, containing small inclusions of oligoclase with albite rims. The groundmass is granular, consisting of altered soda plagioclase and potash feldspar in about equal proportions. The soda plagioclase is commonly zoned with an altered core of more calcic plagioclase rimmed by clear albite. Quartz occurs in irregular grains showing slight strain extinction. *Biotite* occurs in smaller idiomorphic grains forming less than 10 % of the rock. It is patchily altered, partly or completely, to chlorite though some grains appear entirely unaltered. 2714 : 1518 (R. A. G.)



LOCATION IN SPITSBERGEN

OF SAMPLES USED FOR

RADIOMETRIC AGE DETERMINATIONS

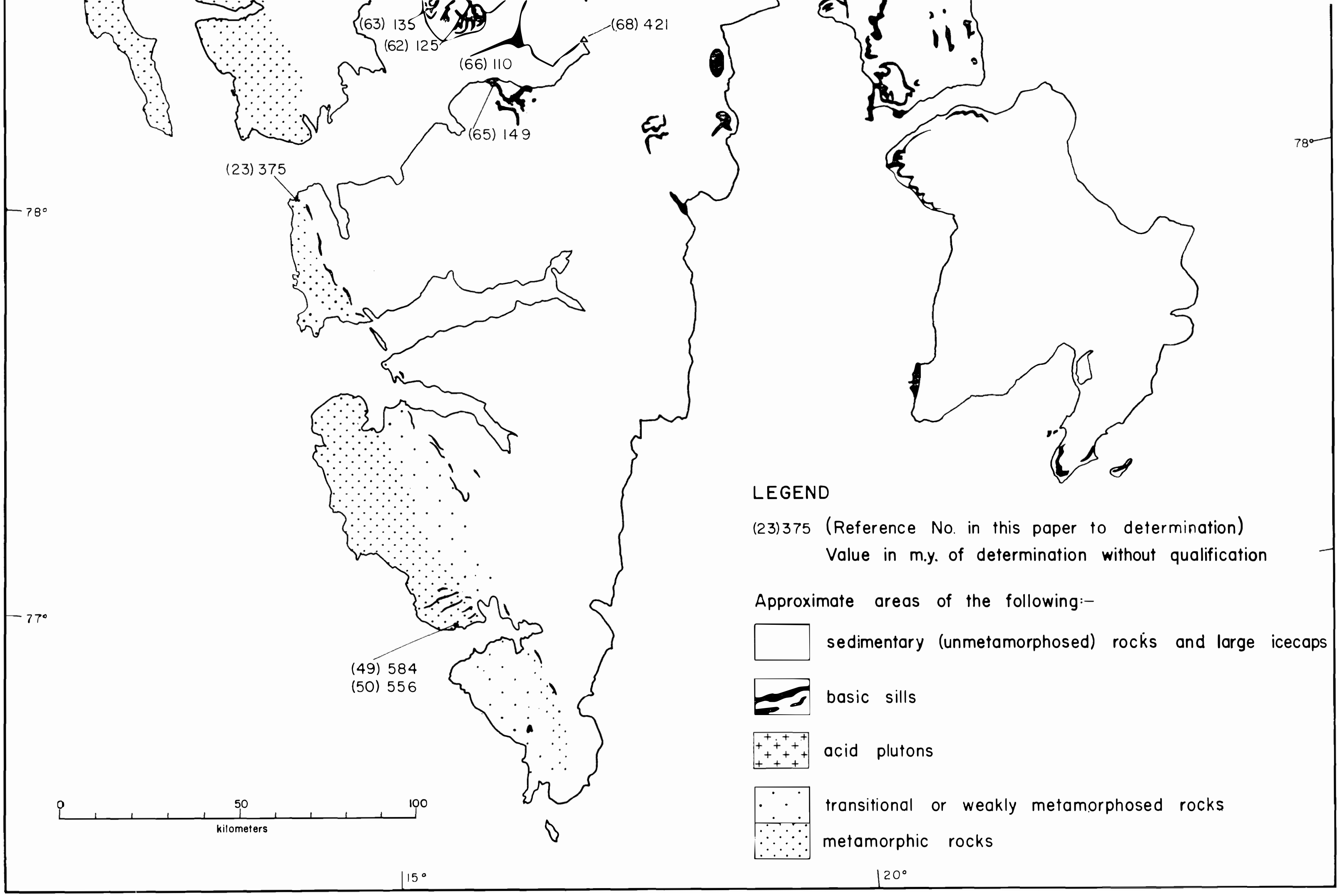


Fig. 1. Location in Spitsbergen of samples used for radiometric age determinations.

(6), (7), (9), (10), (11), (12). Medium grained foliated biotite quartzo-feldspathic semipelite. The rocks consist of about 50 % of discrete grains of patchily altered oligoclase surrounded by a fine grained, granulated mosaic of quartz, forming about 30 % of the rock. *Biotite* partly, and sometimes completely, altered to chlorite occurs in definite bands forming a poorly foliated schistosity which is deflected around the oligoclase grains, many of which have a narrow envelope of fine grained chlorite and biotite. Iron ore and zircon are present as accessory minerals. The fabric of the rock approaches a mortar texture, suggesting the disruption and recrystallization of the quartz and micas under shearing stress. (R. A. G.)

(8). Determination (8) is given in Item 4 of *"Geological Society Phanerozoic time-scale 1964"* from HAMILTON *et al.* 1962 as "Hecla Hoek mica schist (biotite)" but it is in fact *muscovite* from a marginally foliated, very coarse grained pegmatite. The books of mica are up to 1—2 cm thick, and the foliation parallels that in the associated gneisses. 36152: 04744 (D. G. G.)

(47). A coarse grained granular granite. The quartz forms large irregular areas showing strain extinction, some showing marginal rims and small patches of recrystallization to a fine grained, unstrained mosaic. The feldspar consists of about equal proportions of perthite and altered soda plagioclase. Some of the plagioclase grains are zoned from a clear albitic rim to a more calcic (andesine) altered core. The *biotite* forms less than 10 % of the rock and occurs in small grains with pleochroism from straw to brown. Most of the grains are altered to chlorite along the cleavages and some of the grains are almost entirely replaced by chlorite. Iron ore and zircon occur in accessory proportions. (R. A. G.)

(48). A 2 cm square book of apparently unaltered *muscovite* from a pegmatite cutting garnetiferous schists. These pegmatites are made up of a coarse intergrowth of quartz, potash feldspar, plagioclase and muscovite with subordinate tourmaline and garnet. They are unfoliated. (T. S.W.)

(49), (50). A fine grained porphyroblastic garnet mica schist. Euhedral, porphyroblastic garnet crystals are much altered to chlorite and calcite. Porphyroblastic, elongate grains of *biotite* occur; they are marginally embayed by small grains of groundmass muscovite but are otherwise very little altered. The groundmass consist of a fine grained muscovite and quartz assemblage, showing a perfect schistosity, which flows around the earlier garnet and biotite porphyroblasts. (R. A. G.)

(51). *Omphacite* from a coarse grained eclogite occurring as an angular block in an agmatite. The clinopyroxene contains some minor hornblende along the cleavages, which proved impossible to separate without excessively reducing the grain size. Later when the omphacite, after removal of all hornblende, was chemically analysed by J. H. SCOON (GEE 1966), the K_2O content was found to be 0.07 % (less by 0.4 % than that shown in Table II). 36135: 04727 (D. G. G.)

(52). *Biotite* from the crenulated hinge of a tightly folded mica schist band. The mica crystallized mimetically, stacking symmetrically about the axial surfaces of the crenulations. Garnet is disrupted by these folds, having grown (along with kyanite and staurolite in associated pelites) during the formation of an earlier schistosity. 36711: 04842 (D. G. G.)

(53). *Hornblende* from a lens containing 95 % coarse grained, equigranular hornblende, and also relic garnet and pale green clinopyroxene. The lens is folded by a major synform but the hornblende does not show the lineation associated with this fold. 36209: 04710 (D. G. G.)

(54). A quartz monzonite with marginal foliation. The rock consists of a coarse grained assemblage of quartz, muscovite and feldspar, with subordinate biotite and chlorite. *Muscovite* occurs in two sizes; as large irregular plates (usually 2—5 mm, but occasionally up to 10 mm) with marginal fragmentation, and as smaller (0.2 to 0.5 mm) crystals, some of which appear to be related to the disruption of the larger grains. (D. G. G.) (T. S. W.)

(55). A coarse grained granite, with orthoclase, albite, quartz, biotite and muscovite. The specimen shows no obvious foliation, and in thin section there appears to be no preferred orientation of the major minerals. *Biotite* occurs as disorientated aggregates (individual crystals up to 1.5 mm) between the feldspars, and is associated with the quartz and subordinate muscovite. It is much altered to chlorite and sericite. In the sample determined about 40 % of the biotite was altering to chlorite. (D. G. G.)

(56). A foliated schistose biotite semipelite, the biotite grains give the rock a distinct foliation, which flows round garnet porphyroblasts. In adjacent lithologies these garnet porphyroblasts contain helicitic inclusions, indicating an earlier crenulated schistosity which has been recrystallized into the new foliation of the groundmass. The *biotite* separated belongs to the later crystallization event. 36629: 12983 (R. A. G.)

(57). A foliated garnet mica schist adjacent to the margin of a metamorphosed ultrabasic dyke. No signs of an earlier schistosity can be seen, and the dyke is closely associated with the schistosity of the enclosing schists. It appears to have been intruded either contemporaneously or after the development of the local structure. The *biotite* thus belongs to a late stage crystallization. 37349: 12451 (R. A. G.)

(58). A foliated, schistose *biotite* semipelitic band within paragneiss. The neighbouring rocks have a well developed gneissosity which is parallel to the schistosity in the semipelitic band. The foliation has developed from an earlier gneissosity by recrystallization parallel to the axial surfaces of the second generation of folds to have affected the unit. 35972: 11856 (R. A. G.)

(59). A potash-feldspar porphyroblastic, *biotite* gneiss with a poorly developed foliated schistosity. As with (58) the foliation has developed from an earlier gneissosity by recrystallization paralell to the second generation fold axial surfaces. 36641: 12948 (R. A. G.)

(60). *Hornblende* from a garnet amphibolite occurring as a massive lenticular body lying concordantly in augen gneisses. Hornblende overgrows garnet and minor relic clinopyroxene. 35610: 04792 (D. G. G.)

(61). *Hornblende* from a foliated garnetiferous amphibolite which occurs as a band 2 m thick concordant to the schistosity in the adjacent semipelites. The hornblende lies in the foliation and is lineated. Garnet porphyroblasts have helicitic fabrics with inclusions of quartz, feldspar and opaque minerals. Post folia-

Table I. Published Radiometric Data.

No. in this paper A	Specimen collected by B	Radiometric data determined by C	Specimen No. D	Location E	Rock type F	Material analyzed G	% K_2O H	Ar^{40*} (Vol mm^3) I	RB (ppm) J	Sr (ppm) K	Sr^{87} L	Apparent age and error (million years) M
HAMILTON *et al.* [Constants K-Ar: $\lambda_\beta = 4.72 \times 10^{-10}yr^{-1}$; $\lambda e = 0.584 \times 10^{-10}yr^{-1}$; Rb-Sr: $\lambda = 1.47 \times 10^{-11}yr^{-1}$]												
1.	W. B. Harland	D. York (Oxford)	H 626	Eplet, Kvitbreen Ny Friesland	unfoliated porphyritic granite	biotite	—	—	—	—	—	385
2.	»	E. I. Hamilton (Oxford)	»	»	»	»	—	—	1240	15.4	2.08	401 ± 8
3.	»	»	»	»	»	»	—	—	1270	16.3	2.14	402 ± 8
4.	»	J. A. Miller (Cambridge)	H 629	»	»	»	7.35	0.1087	—	—	—	388 ± 14
5.	»	»	»	»	»	»	7.35	0.1150	—	—	—	406 ± 15
6.	»	»	H 829	West shore, Raudfj. at Konglomeratodden	foliated biotite semi-pelite	»	6.07	0.0899	—	—	—	389 ± 14
7.	D. G. Gee	»	E 275	Lagercrantzfjellet, West Raudfjorden	»	»	5.65	0.0935	—	—	—	384 ± 13
8.	»	»	E 686	North Richardvatnet	pegmatite	muscovite	9.42	0.1486	—	—	—	425 ± 22
9.	W. B. H.	E. I. Hamilton	H 828	West shore, Raudfj.	foliated biotite semi-pelite	biotite	—	—	515	25.8	0.82	382 ± 8
10.	D. G. G.	»	E 276B	Lagercrantzfjellet, West Raudfjorden	»	»	—	—	541	7.1	0.86	379 ± 6
11.	»	»	»	»	»	»	—	—	542	7.3	0.86	380 ± 6
12.	»	»	»	»	»	»	—	—	541	8.8	0.85	375 ± 6
HAMILTON and SANDFORD [Constant Rb-Sr: $\lambda = 1.47 \times 10^{-11}yr^{-1}$]												
13.	(by or for) K. S. Sandford	E. I. Hamilton (Oxford)	37	(Nordaustlandet) Isispynten	gneiss	biotite	—	—	588	24.0	1.01	411 ± 7
14.	»	»	7	»	»	»	—	—	533	38.3	0.83	358 ± 8
15.	»	»	20	»	»	»	—	—	646	30.4	1.04	415 ± 10
16.	»	»	3	Duvefjorden	»	»	—	—	699	7.4	1.10	374 ± 6
17.	»	»	42	"Southern Land"	granite aplite	muscovite	—	—	1370	0.1	2.17	378 ± 7
18.	»	»	48	»	granite pegmatite	»	—	—	1047	0.6	1.64	373 ± 10
19.	»	»	51	Nordkapp	granite pegmatite	feldspar	—	—	84	51.2	0.19	537 ± 31
20.	»	»	106	Rijpdalen	schist	biotite	—	—	681	33.6	1.77	618 ± 11
21.	»	»	»	»	»	muscovite	—	—	234	90.5	0.62	636 ± 20
22.	»	»	»	»	»	whole rock	—	—	306	99.0	0.75	581 ± 19

KRASIL'SCHIKOV *et al.* [Constants K-Ar: $\lambda_\beta = 4.72 \times 10^{-10}yr^{-1}$; $\lambda e = \lambda k = 5.57 \times 10^{-11}yr^{-1}$, recalculated $\lambda k = 5.84 \times 10^{-11}yr^{-1}$]

A	B	C	D	E	F	G	H	I	J	K	L	M	recalculated age
23.			5—2	S.W. Coast of Isfjorden	phyllite	whole rock	2.43	4.0	—	—	—	390	375
24.			16—6	S. Coast of Smeerenburgfjorden	alaskite	»	4.05	6.03	—	—	—	355	340
25.			012	Smeerenburgfjorden	gravel from coast plain	»	1.78	2.8	—	—	—	375	360
26.			64—2	Danskøya	biotite gneiss	biotite	6.26	11.40	—	—	—	405	410
27.			38—3	»	biotite granite	whole rock	3.45	5.72	—	—	—	390	375
28.			38—3	»	granite	biotite	5.60	10.0	—	—	—	420	400
29.			42—2	»	granodiorite	whole rock	2.31	3.92	—	—	—	400	385
30.			48—2	»	pegmatite	biotite	6.83	12.9	—	—	—	440	420
31.			64—4	»	»	»	6.74	13.6	—	—	—	455	450
32.			96—1	Verlegenhuken	biotite gneiss	whole rock	4.01	6.4	—	—	—	380	365
33.			75—2	S.W. Coast Bockfjorden	2 mica plagioclase granite	»	2.63	4.20	—	—	—	385	365
34.			75—2	»	plagioclase granite	biotite	3.24	5.25	—	—	—	385	365
35.			102—1	E. Coast of Rijpfjorden (Vinbukta)	2 mica granite (grey)	wholerock	4.72	7.4	—	—	—	375	355
36.			103—1	Vinbukta	2 mica granite (pink)	»	4.63	7.2	—	—	—	370	355
37.			109—1	»	porphyritic granite	»	4.70	7.0	—	—	—	355	340
38.			110—5	»	granosyenite	»	4.67	7.1	—	—	—	360	345
39.			101—6	»	pegmatite	muscovite	8.05	13.6	—	—	—	395	380
40.			125—2	E. Coast of Rijpfjorden Wordiebukta	porphyritic biotite granite	whole rock	4.47	7.27	—	—	—	395	370
41.			4309	Wordiebukta	biotite gneiss	biotite	6.84	13.28	—	—	—	455	430
42.			126—1	E. Coast of Brennevinsfjorden Zeipelbukta	biotite rapakivi granite	whole rock	5.43	9.8	—	—	—	415	405
43			126—1	Zeipelbukta	rapakivi granite	biotite	7.19	12.0	—	—	—	395	380
44.			143a	»	medium grained biotite granite	whole rock	5.26	9.3	—	—	—	410	400
45.			»		medium grained granite	biotite	7.12	12.2	—	—	—	405	385
46.			0126	»	gravel of coast plain	whole rock	4.43	8.3	—	—	—	430	420

Table II. New Radiometric Data

All Radiometric Data determined by J. A. Miller. [Constants $\lambda_\beta = 4.72 \times 10^{-10}yr^{-1}$; $\lambda e = 0.584 \times 10^{-10}yr^{-1}$]

No. in this paper	Specimen collected by K_2O determination by	Specimen No.	Location	Rock type	Material analyzed	K_2O %	% Atmos Contamination	Sv	St	Vol. of radiogenic argon mm^3 at N.T.P. per gm of sample	Apparent age and error (million years)
47.	P. F. Friend J. Matson	F 1367(a)	Smeerenburgbreen	unfoliated granite	altered biotite and chlorite	2.06	8.8	0.6	2.93	0.02357	318 ± 29
48.	T. S. Winsnes J. M.	X 700	West Beverlysundet Nordaustlandet	muscovite from granite pegmatite	muscovite	10.50	—	—	—	0.1701	435 ± 39
49.	W. B. Harland J. M.	H 1096(a)	Polish I. G. Y. base Hornsund	garnet mica schist	biotite	5.36	3.2	—	—	0.1213	584 ± 25
50.	W. B. H. J. M.	H 1096(b)	»	garnet »	»	5.36	1.5	—	—	0.1148	556 ± 24
51.	D. G. Gee J. M.	E 952	North of Richardvatnet N. Haakon VII Land	eclogite	clinopyroxene (omphacite)	0.110	7.5	—	—	0.01232	1939 ± 121
52.	D. G. G. J. M.	E 485	South of Biskayerhuken N. Haakon VII Land	mica schist	biotite	5.81	0.8	—	—	0.09295	431 ± 20
53.	D. G. G. J. M.	E 1110	North of Richardvatnet N. Haakon VII Land	hornblendite after eclogite	hornblende	0.622	10.3	—	—	0.001288	541 ± 24
54.	T. S. W. D. G. G.	X 705	Head of Wahlenbergfjorden, Nordaustlandet	marginally foliated granite	muscovite	6.56 ± 0.04	0.7	2.1	3.70	0.09995	412 ± 19
55.	T. S. W. D. G. G.	X 707	West Beverlysundet Nordaustlandet	unfoliated pink granite	biotite partly altered to chlorite	3.69 ± 0.07	5.6	1.9	3.93	0.05298	391 ± 17
56.	R. A. Gayer »	R 720	East end of Ingstadegga N. W. Ny Friesland	garnet mica schist	biotite	7.72 ± 0.07	0.9	1.1	3.85	0.1198	419 ± 5
57.	R. A. G. »	R 698	North of Mosselbukta N. W. Ny Friesland	mica schist	»	8.12 ± 0.07	2.9	1.8	3.92	0.1283	426 ± 8
58.	W. O'Beirne R. A. G.	O 151	Femmilsjøen N. W. Ny Friesland	paragneiss	»	8.03 ± 0.07	6.4	2.1	4.11	0.1304	436 ± 9
59.	R. A. G. »	R 571	East end of Ingstadegga N. W. Ny Friesland	»	»	7.56 ± 0.06	3.4	1.6	4.0	0.1221	434 ± 7
60.	D. Constable D. G. G.	D 613	N. side of Rabotdalen N. Haakon VII Land	amphibolite after eclogite	hornblende	1.14	6.4	—	—	0.02302	529 ± 15
61.	D. G. G. »	E 806	West Lingfjellet N. Haakon VII Land	amphibolite	»	0.91	38.4	—	—	0.01274	382 ± 12

62. H. R. Spall »	MS 378 (HS 6)	Kapp Thordsen Dickson Land	dolerite	whole rock	0.51 ± 0.1	13.5	17.4	0.8	0.002176	125 ± 12
63. H. R.S. »	MS 5400.3 (HS 4)	Tschermakfjellet Dickson Land	»	»	0.67 ± 0.05	30.6	9.6	1.30	0.003109	149 ± 17
64. J. L. Cutbill H. R. S.	(HS 3)	Gyldenøyane Wahlenbergfjorden Nordaustlandet	»	»	0.61 ± 0.03	38.7	8.2	1.39	0.00302	144 ± 13
65. H. R. S. »	MS 393.4 (HS 5)	Diabasodden Isfjorden	»	»	0.63 ± 0.02	46.6	11.6	1.43	0.003239	149 ± 17
66. H. R. S. »	MS 389.2 (HS 2)	Anservika Bünsow Land	»	»	1.08 ± 0.04	37.5	8.5	1.06	0.004028	110 ± 10
67. W. B. H. R. A. G.	H 1456	N. shore of Adolfbukta Nordenskiöldbreen	garnet mica schist	biotite	7.48 ± 0.035	0.3	1.6	3.78	0.1170	422 ± 6
68. W. B. H. R. A. G.	H 1479	Tunabreen — north lateral moraine	unfoliated granite	»	7.03 ± 0.08	4.1	2.7	3.78	0.1097	421 ± 11
69. D. G. G. »	E 658	North of Richardvatnet N. Haakon VII Land	gneissose amphibolite	hornblende	1.62	5.3	—	—	0.02577	428 ± 17
70. R. G. Mason D. G. G.	M 1669	»	eclogite	clinopyroxene	0.059	45.0	—	—	0.001541	780 ± 50
71. R. G. M. D. G. G.	»	»	»	»	0.059	48.3	—	—	0.001983	813 ± 54
72. D. G. G. »	E 1175	South of Richardvatnet N. Haakon VII Land	»	»	0.199	12.4	—	—	0.04471	1430 ± 8
73. D. G. G. »	»	»	»	»	0.199	17.1	—	—	0.04401	1393 ± 14
74. D. G. G. »	E 1053(a)	South side of Rabotdalen N. Haakon VII Land	biotite amphibolite after eclogite	hornblende	1.01	60.5	—	—	0.01425	389 ± 10
75. D. G. G. »	E 1053(b)	»	»	biotite	5.96	35.5	—	—	0.08798	399 ± 5
76 M. D. Fuller D. Bates	L 171	Krosspynten Wijdefjorden	monchiquite	»	9.41	12.2	—	—	0.1045	309 ± 5

tion biotite porphyroblasts grow across the hornblende and there is minor chloritization of this biotite and of garnet. 36749: 04626 (D. G. G.)

(62), (63), (64), (65), (66). Medium grained varieties of *dolerite* formed essentially of plagioclase and pyroxene. Some subhedral plagioclase phenocrysts of bytownite exist. The relationship with pyroxene is usually ophitic, and these laths are nearer labradorite. Pyroxene has a very low optic axial angle indicating enstatite-augite or pigeonite. Some colourless forms with parallel extinction may indicate orthopyroxene. Occasional brown serpentine occurs after olivine. This is associated with pyroxene and clots of magnetite. The groundmass occurs in isolated areas and is sometimes glassy; it consists mainly of plagioclase laths, pyroxene altering to chlorite mosaics, apatite needles and rods of iron ore. Most of the rock is altered. Clouding of feldspars occurs. Pyroxene and plagioclase are replaced by calcite, and pyroxene also alters to chlorite. In some cases fibrous intergrowths of zeolite occur. Reflected light and X-ray diffraction studies indicate that the iron ore occurs in the form of magnetite-ilmenite intergrowths, and these are altered along the margins to maghemite. Fine grained and marginal varieties of the dolerite do not show extensive alteration. They are characterized by either ophitic or intergranular textures. Plagioclase is labradorite in composition and pyroxene generally pigeonite. Both appear to be fresh. However, the availability of potassium from such varieties is generally insufficient for radiometric purposes. (H. R. S.)

(67). A medium grained porphyroblastic garnet mica schist. The porphyroblasts consist of large subhedral grains of garnet with inclusions of quartz and iron ore forming a straight or slightly folded helicitic fabric. The porphyroblasts are commonly surrounded and embayed by a granulose quartz mosaic. The groundmass consists of quartz and altered plagioclase forming a granular fabric, with biotite and muscovite forming a well developed crenulated schistosity, which flows around the garnet porphyroblasts. *Biotite* slightly exceeds muscovite and both are unaltered. The determined biotite was formed during the final period of recrystallization. (R. A. G.)

(68). A coarse grained, granular granite. Quartz occurs as clear grains showing only slight strain extinction, and forming in the interstices between larger feldspar grains. Potash feldspar showing microcline twinning occurs in excess of plagioclase, both being altered. The larger potash feldspar grains contain small inclusions of altered plagioclase with clear albitic rims on to the potash feldspar. The larger plagioclase grains are commonly zoned from an altered more calcic core to a clear albitic rim. *Biotite* constitutes less than 10 % of the rock, forming small idiomorphic grains, which are slightly altered to chlorite along the cleavages. Hornblende forms small euhedral crystals in about equal proportions to the biotite. Sphene and zircon are present in accessary amounts. (R. A. G.)

(69). *Hornblende* from a gneissose amphibolite which has been isoclinally folded and refolded by late concentric folds. The hornblende is of variable grain size (0.1—2.0 mm), and overgrows the very subordinate green clinopyroxene, and is intergrown with biotite, which may in part replace it. 36084: 04623 (D. G. G.)

(70/71). *Omphacite* from the centre of a coarse grained eclogite occurring as a lenticular mass in amphibolites and quartz feldspathitic gneisses. The omphacite is only very slightly altered to amphibole but a finely disseminated opaque mineral occurs in cracks. 36039: 04733 (D. G. G.)

(72/73). *Omphacite* from a coarse grained eclogite located about 30 metres from an important fault. The omphacite is cracked and is approximately 20 % altered to hornblende, and the analysed sample contained some very minor hornblende in the cleavages. 34816: 04795 (D. G. G.)

(74/75). *Hornblende* (74) and *biotite* (75) from a biotitic amphibolite occurring as a coarse grained, lenticular mass interbanded with feldspathic semipelites. A neighbouring hornblendite lens has a centre of diopside-plagioclase symplectite. The biotite grows across the hornblende. 35582: 04867 (D. G. G.).

(76). A fine grained, porphyritic, partly crystalline monchiquite. The phenocrysts consist of large rounded clinopyroxene grains having reaction rims with the groundmass. *Biotite* occurs in fairly small idiomorphic grains with pale straw to red brown pleochroism and as fresh, larger grains embayed by the groundmass. Clear euhedral crystals of medium grain size occur, completely altered to calcite and zeolite. Lath shaped clinopyroxene grains occur scattered throughout the partly glassy groundmass. (R. A. G.)

Discussion

RELIABILITY OF RADIOMETRIC VALUES AS A MEASURE OF AGE

Before using the radiometric data to interpret events some comment is necessary on the reliability of the results and on their mutual compatibility.

Collecting

Geological collections made by the Cambridge expeditions have not always been primarily for radiometric work (note also similar comments by HAMILTON and SANDFORD 1964, and KRASIL'SCHIKOV *et al.* 1964), and consequently some of the material was not petrographically suitable for age determination work.

Analytical method

The reliability of the values is indicated by the standard error, where available, as given in Tables I and II. The standard error refers only to analytical errors.

Cambridge potassium-argon laboratory procedure has been described by MILLER and BROWN (1964) and errors have been assessed by MILLER and FITCH (1964). Recent advances in instrumentation used are to be described by R. L. GRASTY (in preparation). The rubidium-strontium method used for determinations in Oxford by HAMILTON *et al.* (1962) and HAMILTON and SANDFORD (1964) have been described in Moorbath (1964). The potassium-argon methods used in Leningrad by Krasil'schikov *et al.* (1964) have been briefly described in their paper.

No errors greater than those of the analytical methods are believed to exist between the results of the three laboratories.

Decay constants

The choice of the various decay constants in use affects the value of the apparent age, but within this paper consistency has been achieved by applying the same constants throughout, which are those also used in *"Geological Society Phanerozoic time-scale 1964"*. Thus the K-Ar values for Krasil'schikov *et al.* (1964) have been recalculated from tables in Smith (1964) using the constants $\lambda_\beta = 4.72 \times 10^{-10} \mathrm{yr}^{-1}$ and $(\lambda\ k) = \lambda_e = 0.584 \times 10^{-10} \mathrm{yr}^{-1}$, which thus allows direct comparison to be made between the Russian data and the determinations made in Oxford and Cambridge. Mutual compatibility of results by K-Ar and Rb-Sr methods using the constants quoted above for the former, and $\lambda = 1.47 \times 10^{-11} \mathrm{yr}^{-1}$ for the latter, has been demonstrated by many workers (Zartman 1964). Values for rubidium-strontium decay constants have been discussed by Moorbath (1964).

Mineralogy

The remaining and, perhaps, principal error which makes all values apparent ages, rather than true ages, stems from the crystal history of the minerals analysed. This depends on the individual circumstances which are discussed below.

Pyroxene

The determinations (51), (70), (71), (72), (73) were made on omphacitic clinopyroxenes from North Haakon VII Land. The ages range from 780—1939 million years (m. y.) yet the samples determined came from the same formation (Gee 1966). From a K_2O analysis (Gee 1965) of (51) it is likely that the 1939 m. y. determination is too low (see p. 10). Hart and Dodd (1962) and McDougall and Green (1964) have drawn attention to the unreliability of K-Ar determination on some metamorphic pyroxenes due to the presence of possible excess radiogenic argon, and similar unreliable results have been obtained by two of us (D. G. G. and J. A. M.) on Lewisian clinopyroxenes from north Scotland. The age determinations on the omphacites are therefore considered not to represent the age of crystallization of the eclogites.

The results are thus inconclusive and they neither support an "Archaean" age nor, with any certainty, a Caledonian age.

Hornblende

Various authors have commented on the reliability of hornblende ages in elucidating crystallization sequences in areas subjected to superimposed metamorphic episodes (e. g. McDougall and Green 1964), and on the good retentivity of radiogenic argon by hornblendes which have not undergone chloritization (ZARTMAN 1964). An investigation of the retentivity of argon by hornblende when reheated in the contact aureole of a granite plug led HART (1964) to propose the possibility of two lattice sites for radiogenic argon in hornblendes, the one containing 85 % of the argon and being highly retentive (the loss of argon not occurring until the reaction to biotite) and the rest, 15 %, being expelled from the other lattice site by only mild heating.

In North Haakon VII Land amphibolization of the eclogites occurred during a regional metamorphism which affected all lithologies present (GEE 1965). Determinations (53) and (60) were made to investigate the age of this crystallization episode. The specimens were selected from widely separated areas (6 km apart) and the potash contents of the hornblendes were found to be very different. The ages obtained from these samples (529—541 m. y.) overlapped within the limits of the estimated analytical error. This agreement favours the assumption that these ages are related to the time of crystallization and are not due to incorporation of excess radiogenic argon from the parent pyroxenes. However, both samples are from areas subjected to later metamorphism (at about 430 m. y.) and loss of some radiogenic argon is possible. In the light of HART's work on the argon retentivity of hornblende one of us (D. G. G.) calculates (by addition of 15 % radiogenic argon) a probable age of ca. 600 m. y. for the time of the regional metamorphism causing the amphibolization of the eclogites.

The age of 428 m. y. on hornblende from a gneissose amphibolite (69) showing folding and recrystallization during the main superimposed metamorphic episode in the area, compares closely with that of 431 m. y. from a biotite (52) recrystallizing during the same metamorphism.

One sample (74), (75) was selected from an eclogite, 500 m from the unconformity between the post-crystalline Siktefjellet Group and the crystalline rocks in west Rabotdalen. The eclogite shows retrogression to amphibolite, and later biotite crystallized discordantly across the hornblende. Post-crystallization deformation is notable in this area. Nevertheless the ages of the biotite and of the hornblende are closely comparable (389 and 399 m. y. respectively). A hornblende determination was made on an amphibolite (61) which possessed biotite porphyroblasts and a lower age of 382 m. y. was obtained.

Biotite

Under normal conditions biotite has a good retentivity of radiogenic argon but under conditions of post-crystalline deformation or heating, or of leaching, it is susceptible to loss of radiogenic argon (MILLER and FITCH 1964).

Age determination errors due to leaching have been investigated by KULP and ENGELS (1963). Argon and potassium substitute for each other in the biotite lattice, and it has been demonstrated that the loss of the first 80 % of the potash is accompanied by approximately equal loss of radiogenic argon. Thus in biotites subjected only to leaching the age is unlikely to be much affected, though KULP and ENGELS suggest that biotites containing less than 6 % potash should be treated with reserve.

Samples (56), (57), (58), (59) are obtained from across a wide area of northwest Ny Friesland. Sample (52) comes from north Haakon VII Land, and (67) from western Olav V Land. All determinations are on fresh, unchloritized biotites and give mutually consistent results (419—436 m. y. mean 428 ± 9 m. y.).

(47) is highly chloritized and has a low potash content (2.06 $^{0}/_{0}$), and the apparent age is low even in comparison with neighbouring acid whole rock ages (24), (25). (55) is highly chloritized and is thus also likely to give a low apparent age.

Determinations (6), (7), (9), (10), (11), (12) from the west coast of Raudfjorden, show some signs of post-crystallization fabric disruption which results in the partial chloritization of biotite. The apparent ages determined by both Rb-Sr and K-Ar methods lie between 375—389 m. y., which is lower than the group of unretrogressed biotite ages (52), (56), (57), (58), (59), (67) c. 428 ± 9 m. y. but is similar in age to that obtained from two amphibolites showing growth of late biotite, (61), (74), (75) c. 390 m. y.

Post-biotite deformation or recrystallization, giving rise to probable loss of radiogenic argon, affected determinations (49) and (50) which have been involved in the intense Tertiary west coast folding (Orvin 1940, Harland 1961), superimposed on the Caledonian crystallization.

Muscovite

Radiogenic argon retentivity is usually slightly higher in muscovite than biotite (Hart 1964, Miller and Fitch 1964). Some radiogenic argon loss is suspected in (8) due to cataclasis, and the age of intrusion is not given by this apparent age. In sample (54) the biotite is heavily chloritized and some loss of radiogenic argon may have occurred in the muscovite.

Feldspar

No K-Ar determinations have been made in Cambridge on separated feldspars. Feldspars appear to be reliable for the Rb-Sr method (Moorbath 1964) and one determination has been made (19).

Acid igneous rocks — whole rock method

Miller and Fitch (1964) have discussed the suitability of K-Ar whole rock determinations. The relative retentivity of radiogenic argon in such samples is dependent upon that due to the individual mineral phases and that due to the fabric of the rock. The potassium bearing, and hence radiogenic argon bearing, minerals of acid igneous rocks are in the main alkali feldspars, and biotite and muscovite micas. The radiogenic argon retentivity of the micas has been discussed above. Many workers (see Table 4 in Miller and Mussett 1963, and Miller and Fitch 1964) have shown that the radiogenic argon retentivity of feldspars, and especially of orthoclase and microcline, is often very poor, hence the apparent ages obtained by the Russian workers with the K-Ar method on the whole rock samples (23), (24), (25), (27), (29), (32), (33), (35), (36), (37), (38), (40), (42), (44), (46) may well be too low.

Basic igneous rocks — whole rock method

McDougall (1961) showed that the whole rock potassium argon method could satisfactorily be used to find the apparent ages of basic intrusions. However, variable ages have been obtained from synchronous basic igneous intrusions. Miller and Musset (1963) showed that one reason for this is the amount of alteration of the groundmass. Electron probe methods show that most of the potash of basic igneous rocks is held in the groundmass interstices and mesostasis and thus alteration causes significant losses in the very small amounts of potassium and radiogenic argon present leading to low apparent ages. The reliability of whole rock basic igneous determination is further discussed in Miller and Fitch (1964). Thus the spread of ages 149—110 m. y. of the Spitsbergen Mesozoic dolerites (62), (63), (64), (65), (66) is correlated with variation in alteration. It is likely that the significant apparent age is the oldest determined, i.e. (65) 149 m. y. (See Miller and Fitch 1964).

One of us (H. R. S.) suggests that in these dolerites there may be a relationship between degree of alteration and depth of burial. In this case it happens that around Isfjorden (62), (63), (65), (66) the youngest ages are recorded from dolerites intruded into the oldest sediments. Investigations by H. R. S. also show that the most reliable palaeomagnetic information is obtained from the least altered dolerites, which are usually those of finest grain size.

Recent gravels — whole rock method

Although (25) and (46) are from gravels, probably largely consisting of Caledonian crystalline rocks, we do not use these values further in this paper as we have too little information.

TIME-RELATIONS OF PETROGENESIS

This section considers the times the minerals are thought to have crystallized in relation to various petrogenetic events, with special reference to the material in Table II.

Metamorphic rocks

North-east

The regional metamorphism in the areas of Wahlenbergfjorden and west Beverlysundet must have preceded the intrusion of the acid igneous plutons. Two of the three samples of these intrusive rocks (54) and (55) have suffered some post crystallization deformation and the third (48) is subject to a large analytical error. These three apparent ages 391 ± 17, 412 ± 19 and 435 ± 39 m. y. thus set a lower limit to the age of metamorphism.

This minimum age, together with Rb-Sr apparent ages of 411 and 415 m. y. (13), (15) from Isispynten in the far east of Nordaustlandet, and with the K-Ar apparent age of 430 m. y. (41) from Rijpfjorden, suggests that a very extensive area of Nordaustlandet underwent recrystallization, at least of biotite grade, at about the same time as similar events to the west e. g. (52), (56), (57), (58), (59), (67).

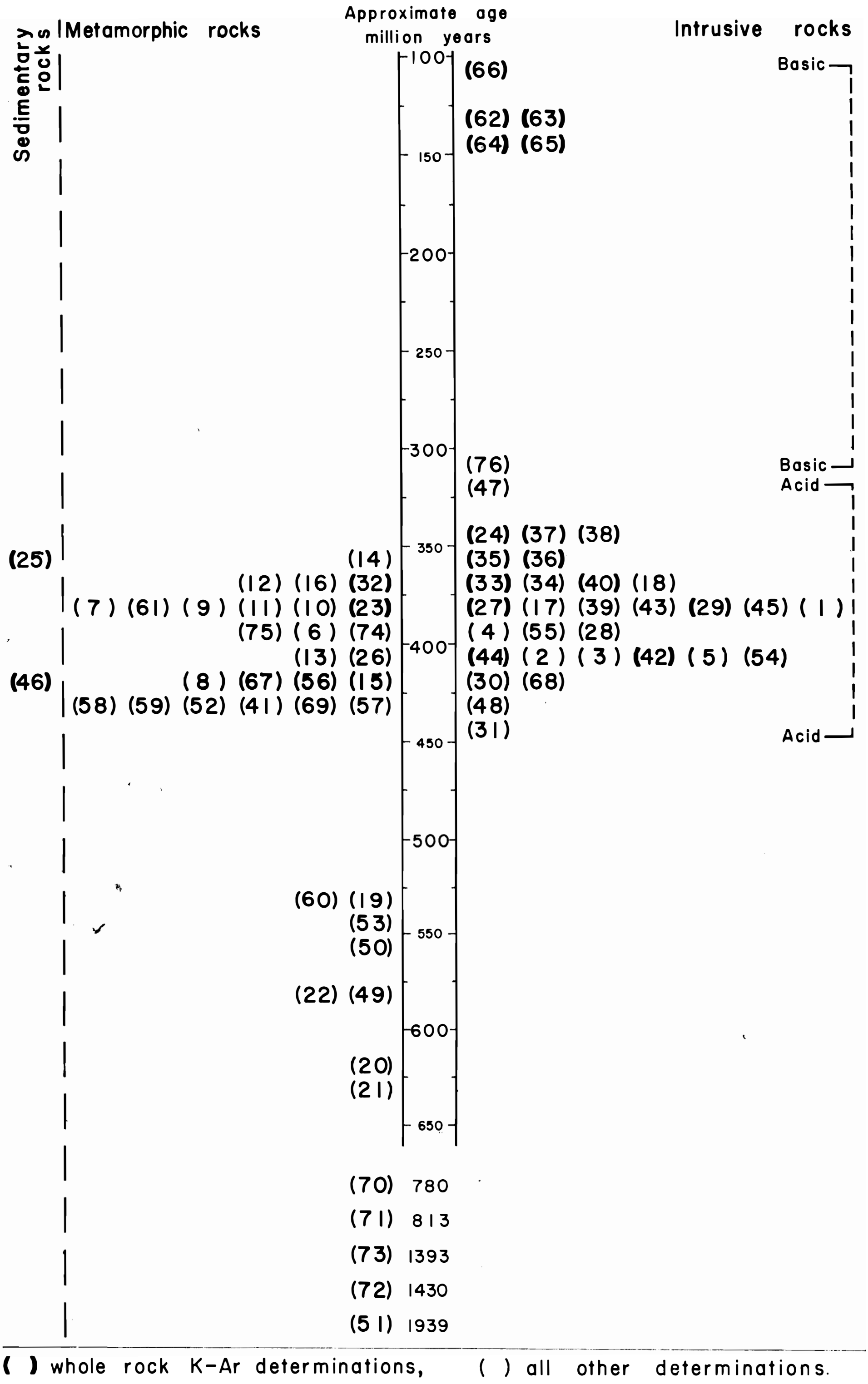


Fig. 2. Reference numbers of radiometric determinations in geochronological order.

Inner Rijpdalen has been investigated by one of us (T. S.W.). The area consists of quartzites and schistose phyllites with lithologies comparable to the lowermost Murchison Bay Formation and to the Kap Hansteen Formation (KULLING 1934). The phyllites were found to be transitional to granite gneisses. The latter are thought to represent granites intruded prior to folding, and deformed with the quartzites and phyllitic schists to form foliated gneisses. No "archaean basement complex" has been located. The apparent age of the schists has been determined by Rb-Sr methods (20), (21), (22) which give an apparent age of c. 600 m. y. The associated granite gneisses have also been determined by K-Ar methods and give an apparent age of 430 m. y. (41). (20), (21) and (22) may represent an "Archaean" basement overprinted by Caledonian metamorphism (HAMILTON and SANDFORD 1964) or older Hecla Hoek rocks metamorphosed (with or without overprinting) in late Pre-Cambrian time. (See Discussion, p. 31).

North-centre

The four northern Ny Friesland specimens (56), (57), (58), (59) 419—436 m. y. were selected to establish the age of the final recrystallization of biotite in this area. No attempt was made to date individual stages during the Ny Friesland orogeny, although this might be possible, and the specimens were collected from various formations (acid gneisses to pelitic schists) in different tectonic situations. The biotites do not preserve the earlier stage of recrystallization preserved in the specimens nor do they contain signs of later retrogression.

Specimen (67) 422 m. y. from western Olav V Land also represents the last main phase of metamorphism. The specimen reveals an earlier phase of crystallization which is not present in the biotite determined. Late minor brittle retrogressive structures are present. The specimen is thus from a comparable geological situation to those from northern Ny Friesland.

North-west and south-west

An earlier crystallization event occurred in at least part of the western belt of metamorphic rocks prior to the main phase of the Caledonian metamorphism. This is indicated in the north-west by determinations (53) and (60), apparent ages 541 and 529 m. y. (K-Ar method on hornblendes) and also in the south-west by determinations (49), (50) which give apparent ages of 584 and 556 m. y. (K-Ar method on biotites).

Samples (69) and (52), with apparent ages of 428—431 m. y., would appear to give evidence of the main structural and metamorphic event found elsewhere in Spitsbergen. The muscovite (8) apparent age of 425 m. y. is similar and supports the conclusion that this is the main Caledonian event, comparing closely with the apparent ages from the biotites of Ny Friesland.

Many of the determinations, e. g. (6), (7), (9), (10), (11), (12), (61), (74), (75) made on minerals from metamorphic rocks from the north-west area by both K-Ar and Rb-Sr methods gave apparent ages of less than 400 m. y. (6—7), (9—12) average c. 380 m. y. which HAMILTON *et al.* (1962) suggested corresponds to the last metamorphic event of the Caledonian orogeny. Determinations

(61), (74) and (75) gave apparent ages of 382 ± 12, 389 ± 10 and 399 ± 5 m. y. These two groups will be considered below and are shown in Fig. 3.

As described above (p. 10) the foliated biotite semipelites of the first group have suffered quite extensive post-crystalline deformation and cataclasis, resulting in the granulation of quartz and the retrogression of biotite to chlorite. It is thus probable that the K-Ar apparent ages of (6) 389 ± 14 m. y. and (7) 384 ± 13 m. y., are too low, and equally the mixture of the two generations of biotite and chlorite will result in the redistribution of rubidium and strontium causing the Rb-Sr ages ((9—12) mean 379 ± 4 m. y.) also to be too low. On the other hand this is a closely grouped dating in time of rocks from different localities determined by different methods and should indicate some event. Either this is the completion of the later chloritization reaction of biotite by cataclasis, or, as the biotites are only partly altered, it is possible that the two events — crystallization of biotite and cataclastic production of chlorite — were not far separated in time. The c. 380 m. y. event would thus represent some indeterminate mean between the crystallization of biotite and the time of breakdown to chlorite (by cataclasis).

Of the second group, determination (61) is on a hornblende from amphibolite, and (74) and (75) are on apparently fresh biotite and hornblende from a biotite hornblende rock developed from an amphibolized eclogite. These are minimum ages and could represent a metamorphic episode of 400—390 m. y., or the last effects of the waning thermal environment associated with the main Caledonian metamorphism in the area c. 430—420 m. y. Specimens (74) and (75) occur near a fault zone which also cuts nearby unconformably overlying rocks.

Acid igneous rocks

Under ideal conditions consistent and reliable ages may be obtained from granitic bodies (Zartman 1964). However, it is often extremely difficult to obtain a satisfactory and reliable age from extensive and differentiated acid igneous intrusions (Miller and Mohr 1964). In such cases the oldest apparent age is likely to be the most significant, but even so the true age may be greater (Miller and Fitch 1964).

The Cambridge K-Ar determinations on micas from granites, (47) from the north-west, (4), (5) from the north-centre, and (48), (54), (55) from the north-east, are in all cases slightly suspect, for the biotites are partially chloritized and the muscovites are affected by post crystalline deformation. Therefore, the apparent ages obtained are likely to be minimum ages rather than true ages of crystallization.

The Rb-Sr determinations (17), (18), (19) are of granitic aplites and pegmatites, but no petrographic or field information is available to evaluate their exact significance.

The extensive Russian K-Ar published data on granites suffer the same limitation.

Specimen (68) 421 ± 11 m. y., was collected from the westerly lateral moraine of Tunabreen, where numerous large boulders of unaltered pink to purple medium grained granite are common. No granite is at present seen within the catchment area of the glacier. A representative boulder was sampled and the result reinforces the view that either a continuation of the Nordenskiöldbreen granite extends eastwards below Lomonosovfonna, or another pluton belonging to the same granite series is being unroofed.

Basic igneous rocks

Monchiquite dykes have not previously been recorded from Spitsbergen and will be described in connexion with a study of the geology of Andrée Land by P. F. FRIEND. Biotite phenocrysts from specimen (76) give an apparent age of 309 ± 5 m. y.

The petrography of the dolerites (62), (63), (64), (65), (66) has already been redescribed in this paper. For their field relationships see TYRRELL and SANDFORD (1933), ORVIN (1940), HARLAND (1961), PARKER (1966).

STRATIGRAPHICAL SIGNIFICANCE

Having attempted to eliminate unreliable values and assess the reliability of the remaining ages, it is now possible to consider the events which these represent, in relation to the stratigraphical column. This depends in turn on the reliability of a time scale, calibrating stratigraphical divisions in years. Many such time scales have been attempted and more recently by HOLMES (1959) and KULP (1961). The most recent available to us is "Geological Society Phanerozoic time-scale 1964" which is used here. In constructing that scale some of the data considered in this paper were used for the base of the Devonian, and the further data and discussion here invite some reconsideration.

Because both radiometric and palaeontological correlation prove more difficult with increasing age we begin with the youngest events indicated by the ages so far determined.

Mesozoic events

Extensive dolerite sills (see fig. 1) have long been known to cut Carboniferous Permian, Triassic and Jurassic rocks in Spitsbergen, and their age has been variously estimated on indirect structural and stratigraphical grounds to be late Jurassic (TYRRELL and SANDFORD 1933) or late Cretaceous (ORVIN 1940, HARLAND 1961). Further east, in Kong Karls Land, there is evidence for more than one period of volcanic and intrusive activity (NATHORST 1901, 1910) and the latest lavas overlie rocks of Valanginian age.

The radiometric determinations made in conjunction with a palaeomagnetic study of these dolerites, by one of us (H. R. S.), are widely distributed in space; their apparent ages (62), (63), (64), (65), (66) are plotted in Table III against the relevant Mesozoic stages from "Geological Society Phanerozoic time-scale 1964".

These rocks probably give minimum ages because they are altered in some degree and determined by the K-Ar whole rock method. It is significant that even so all the ages are Pre-Cenomanian (see Table III). Thus the argument

Table III

Apparent ages in this paper plotted against Mesozoic stages adapted from the "Geological Society Phanerozoic time-scale 1964" in m. y.

	Cenomanian		
		100	
	Albian		
		106	
	Aptian		(66) 110 ± 10
		112	
	Berremian		
		118	
	Hauterivian		
		124	
	Valanginian		(62) 125 ± 12
		130	
	Ryazanian		(63) 135 ± 15
		136	
Volgian	Purbeckian		
		141	
	Portlandian		(64) 144 ± 13
		146	
	U. Kimmeridgian		(65) 149 ± 17
	M. & L. Kimmeridgian		
		151	

(Orvin 1940, Harland 1961) that the intrusions might be Upper Cretaceous because of the lack of Upper Cretaceous sediments, is opposed.

In Isfjorden, the dolerites (62), (63), (65), (66) probably represent one phase of intrusion rather than many (Tyrrell and Sandford 1933), the scatter in time here being accounted for by the variation in degree of alteration of the groundmass (see p. 21). On this assumption the oldest date (i. e. 149 m. y. [65] is preferable, and suggests a late Jurassic age. Determination (64) from Nordaustlandet agrees with a late Jurassic age for the Isfjorden dolerites.

Recent structural and stratigraphical work by Parker (1966) on Marmierfjellet gives positive evidence for the age of the Isfjorden dolerites as post-Lower Volgian and pre-Valanginian. Although a sample from Marmierfjellet has not yet been determined, determination (65), which gives the oldest age, comes from related dolerites of the same area. Thus there is general agreement between the new structural and radiometric data for the age of intrusion of the dolerite sills as late Jurassic or early Cretaceous.

Carboniferous events

Monchiquite (lamprophyre) dykes at Krosspynten cut the Keltiefjellet division of the Wood Bay Series (Emsian — Siegenian, i. e. Lower Devonian). Krosspynten is some distance from the Billefjorden Sandstones (Dinantian and Lower Namurian) which overlie deformed and eroded Givetian (Middle Devonian) rocks in the same general fold and fault belt. Determination (76), giving an apparent age of 309 ± 5 m. y., would appear to indicate intrusion in Middle Carboniferous times (see Table IV). This apparent Middle Carboniferous event might correlate with the instability further south along the same fault demonstrated by the presence of the distinctive Pyramiden conglomerates of about the same age.

The lamprophyre dykes of central Ny Friesland are proved stratigraphically pre-Permian but are petrographically dissimilar and are associated with the Caledonian plutons (Harland 1959).

Table IV

Carboniferous time-scale adapted from Francis and Woodland (1964 p. 222) to central Spitsbergen rocks (Harland 1961, p.99).

	....	280 ±	
Upper Carboniferous			Wordiekammen limestones
	....	290—295	....
Middle Carboniferous	Moscovian		Passage Beds
	....	307 ±	Pyramiden Conglomerates
	Bashkirian		Lower Gypsiferous Series
	....	317 ±	....
Lower Carboniferous			Billefjorden Sandstones
	....	345 ±	

Mid-Palaeozoic stratigraphy

It has long been known that Red Bay Series, fossiliferous Lower Devonian strata rest unconformably on metamorphic rocks in the north-west of Spitsbergen. Hamilton *et al.* (1962) attempted to use this relationship to provide a critical limit for the age of the base of the Devonian. Since then Gee and Moody-Stuart (1965) have described the Siktefjellet group (of sandstones and conglomerates) which underlies the Red Bay Conglomerate of the Red Bay Series; the latter were previously assumed to be the oldest overlying rocks. Thus, the youngest valid age of the underlying metamorphic rocks, which are included in the basal conglomerates of the overlying Siktefjellet group, still further limits the age of the base of the Devonian. The field relationships as given by Gee and Moody-Stuart (1966) represent the following sequence of events.

7. Deposition of fossiliferous Fraenkelryggen Division of the Red Bay Series. (Uppermost Downtonian — upper Lower Gedinnian).
6. Deposition of 200 m of Andréebreen sandstone of the Red Bay Series.
5. Deposition of the Red Bay conglomerate.
4. Folding and thrusting, followed by erosion.
3. Deposition of conglomerates and sandstones of the Siktefjellet group.
2. Thrusting, uplift and erosion of several thousand metres of Hecla Hoek rocks.
1. Latest regional metamorphism of Hecla Hoek rocks.

The nature of the conglomerates and sandstones suggests that events 1 to 6 may not be far separated in time. This interpretation suggests that the age of the base of the Devonian in this area is closely related to the age of the last regional metamorphism of the underlying beds, and thus merits further discussion.

We wish first to reject the possibilty that more time could usefully be gained for these events by revising the palaeontological correlation of the Red Bay Series. By using fish faunas White (1956) correlated the Fraenkelryggen division with Upper Downtonian, and Westoll (1951) correlated this horizon with Gedinnian (summarized from Friend 1961). Thus it seems unlikely that the Fraenkelryggen division could be younger than Gedinnian and impossible that the still older Siktefjellet group could be so. Indeed the effect of this consideration is rather to suggest that stratigraphically the pre-Siktefjellet regional metamorphism would have taken place well before the Devonian period.

Estimates for the age of the base of the Devonian made independently, for example by Holmes (1959) and Kulp (1961), gave 400 ± 10 and 405 m. y. respectively and depended heavily on the age of the Shap granite (Geological Society 1964, Item 6) which metamorphoses the lower part of the Ludlow succession and gives an age of 393 ± 11 m.y. (Brown, Miller and Soper 1964). Other relevant granites give a similar age (e.g. Items 5, 93, and 97, Geological Society 1964), the remarkable Kap Franklin (E. Greenland) result (Haller and Kulp 1962 and Geological Society 1964, Item 1) would suggest an age within the Middle Devonian of 393 m. y. Against this Hamilton *et al.* (1962), on the basis of determinations (6), (7), (8), (9), (10), (11), (12), suggested a date for the base of the Devonian of 383 m. y. or less. Friend and House were able to consider all these data in proposing an age of 395 m. y. for the base of the Devonian (in Geological Society 1964).

We now have more information than was available to Hamilton *et al.* (1962) and the interpretation of the metamorphic sequence in the north-west (see p. 18 and 23) might be summarized as follows:

1. c. 430—420 m. y. Main Caledonian crystallization event.
2. c. 420—400 m. y. Possible mimetic crystallization due to waning stages of the above.
3. c. 400 m. y. Possible last localized crystallization phase e.g. (74), (75).
4. c. 390—380 m. y. Possible age of the post crystalline cataclastic deformation leading to production of chlorite from biotite of stage 1, the 383 m. y. event of Hamilton *et al.* (1962).
5. post 400 ± 20 m. y. Post tectonic granite intrusion. (Systematic investigations of the pebble content of the Red Bay conglomerates and the Siktefjellet conglomerates have been made by Holtedahl (1926), Harland (1961), and Gee and and Moody-Stuart (1966) and they concluded that most pebbles indicate metamorphic rocks of Lower Hecla Hoek type. No unfoliated porphyritic, post-tectonic granites were noticed).

To reconcile these conflicting data, especially in relation to the various possible ages for the base of the Devonian, some of the radiometric ages cannot be accepted at their face value and must be rejected. Three possibilities present themselves:

A. By ignoring our c. 380 m. y. local metamorphism, the base of the Devonian might be retained provisionally at 395 m. y. thus following Friend and House

(1964). In this case events 1—7 described on p. 27 occurred in a very restricted time span of about 5 m. y.

B. A younger age for the beginning of the Devonian might be postulated, by adopting the minimum ages for the Shap and related granites and by ignoring the Kapp Franklin granite. In this case even some of the late metamorphism could be accommodated prior to the deposition of overlying rocks.

C. The age of the base of the Devonian might be increased, e. g. to HOLMES' (1959) 400 m. y. or to KULP's (1961) 405 m. y. values, by ignoring our ages for metamorphism, not only at c. 380 m. y. but also at c. 400 m. y., and so accommodating the minimum age for the Kapp Franklin granite.

We have insufficient data to decide between these possibilities and intend to seek more, though on present evidence we consider hypothesis (B) least probable. The age of the Siktefjellet deposits (e. g. whether late Silurian) is related to this question.

Caledonian events

The later stages of Caledonian history are bound up with the local Lower and Middle Devonian sedimentation and with the still later Svalbardian folding which we cannot match with radiometric evidence. The youngest fossiliferous rocks deformed by the main Caledonian movements are of Canadian (L. Ordovician) age as seen in the Upper Hecla Hoek of north-central and south Spitsbergen. According to current time scales the top of the Arenig would be pre-445 and probably post 500 m. y. — say c. 470 m. y.

Most data relate to metamorphism apparently between 450 and 365 m. y. and plutonism apparently between 420 and 340 m. y.; in both cases the lower values are from altered material or K-Ar whole rock determinations on acid material. Most apparent ages fall between 450 and 400 m. y. and fit the stratigraphical gap between Canadian in the north-centre and Devonian (possibly late Silurian) in the north-west. This main Caledonian diastrophism has been termed the Ny Friesland orogeny (HARLAND 1961, p. 82).

Although the present radiometric sampling is inadequate for reliable generalization the metamorphic apparent ages appear to be grouped around two peaks at about 430—420 m. y. and 390—380 m. y.

The concentration of earlier ages at 430—420 m. y., is recorded from Danskøya, in the far west, to Isispynten, in the far east, thus apparently embracing the whole width of Svalbard (ca. 450 km), and this event is interpreted as approximating to the time of the main Caledonian tectogenic phase in Svalbard.

In the north-centre (Western Nordaustlandet, Ny Friesland and Olav V Land) it is thought that this tectogenic event caused a sequence of folding, metamorphism, schistosity, lineation and boudinage.

In the north-west, one of us (D. G. G.) on textural (and other) evidence interprets the dominent schistosity as being related to an early fold sequence and would correlate this with the metamorphic event which may have occurred at c. 600 m. y. (GEE and HJELLE 1965). It is clear, however, that a Caledonian deformation sequence (folding to boudinage) followed by general migmatization has affected most rocks in this north-west area.

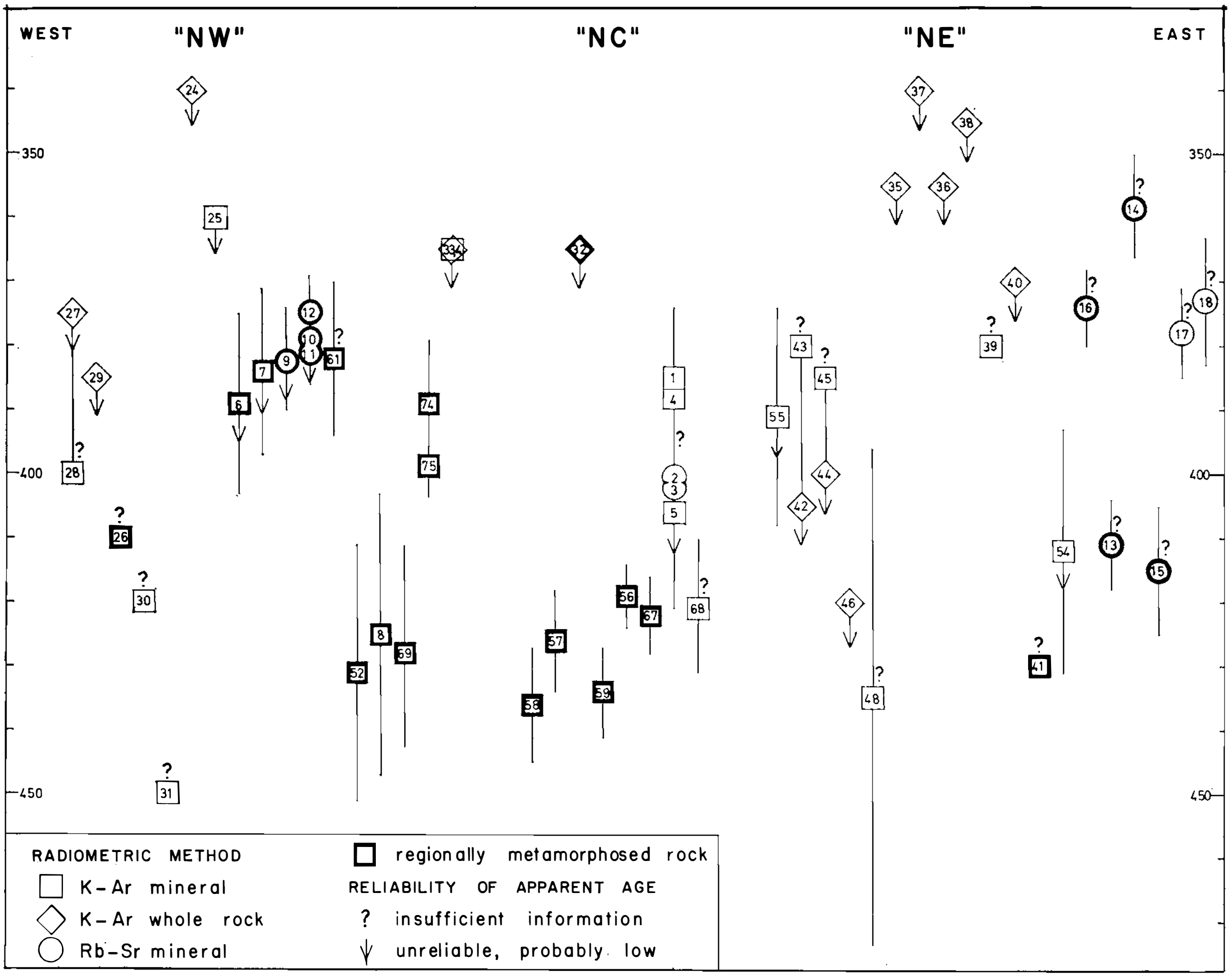


Fig. 3. Distribution of "Caledonian" apparent ages in m. y. from Spitsbergen.

In the north-east (central and eastern Nordaustlandet) our information is more limited. Some parts of Nordaustlandet, e.g. Rijpdalen (Winsnes in press), appear similar to central Ny Friesland, but the older Rb-Sr ages (600 m. y.) allow an interpretation similar to that of central North Haakon VII Land, with similar Caledonian overprinting. In others, e.g. Isispynten (Sandford 1954, Harland 1961 p. 72—3) migmatization is evident, comparable with that of the north-west. Thus an overall symmetrical pattern appears to exist with Caledonian migmatites in both the extreme east and west.

The evidence for late Caledonian, 380—390 m. y. metamorphism comes from the vicinity of Raudfjorden in the north-west. In this area four samples from west of the fjord and two from the east gave K-Ar, and, in the case of the western samples, also Rb-Sr, ages from 399—375 m. y. with a concentration at ca. 380 m. y. It is suggested that this is related to postcrystalline chloritization in an area where evidence of cataclastic metamorphism is widespread.

The time relationship of the post-tectonic granites to the major phase of tectogenesis is not completely clarified by the radiometric data for, unfortunately we are prepared to qualify almost every determination.

The Smeerenburgbreen granite is known (HOEL 1914) to post-date the regional folding and metamorphism and the later regional migmatization of the north-west area. Tentatively in this area we would lay most emphasis on the biotite age (28) of 400 m. y. for the minimum date of the earliest post-tectonic granite. The lack of granite pebbles in the Red Bay conglomerate noted above leaves their stratigraphical relationship unresolved as this could be due to lack of granite exposure at that time rather than later intrusion.

Granites in the north-centre are known to post-date the post-Canadian Caledonian tectogenesis and they are unconformably overlain by unmetamorphosed Permian and Carboniferous (HARLAND 1959). Apparent ages (1), (2), (3), (4), (5), for the Chydenius granite and (68) from a Lomonosovfonna granite do not conflict with this stratigraphical evidence being respectively ca. 405 m. y. and 420 m. y.

The geological situation of the north-east granites is less well described, but there is general agreement that the pink porphyritic granites post-date the folding of the Hecla Hoek, (SANDFORD 1950, 1956, KRASIL'SCHIKOV 1964), and that they are pre-Permian.

As discussed on p. 24, the Brennevinsfjorden granite would appear to have a minimum age of 400 m. y.; the Rijpfjorden granite a minimum age of c. 380 m. y., the granite at the head of Wahlenbergfjorden a minimum age of c. 412 m. y., and the granite of "Southern Land" a minimum age of c. 375 m. y. Determination (19) 537 m. y. from Nordkapp is referred to below.

Cambrian or Pre-Cambrian events

The base of the Cambrian has been variously placed around 570 m. y. (COWIE 1964). Crystalline rocks which yield significant high apparent ages have so far been found in three areas: in the south (Hornsund); in the north-west (south of Biskayerhuken); and in the north-east (north central Nordaustlandet). However, only five rocks need be considered (see Table V). The absence of determinations with similar ages, from the north-centre, may not be significant, as rocks which may have preserved a pre-Caledonian texture and mineralogy have not yet been determined.

The most complete succession of Hecla Hoek rocks so far known is recorded from the north-centre (which includes the type area, HARLAND 1961). No conspicuous break has yet been demonstrated there in a succession which ranges down through Lower Ordovician and Cambrian carbonates, through Varangian (tillite bearing) clastics (all Upper Hecla Hoek) and then through more than ten kilometres of Middle and Lower Hecla Hoek, the Lower Hecla Hoek being strongly metamorphosed (HARLAND and WILSON 1956).

A similar succession extends across to the north-east (e.g. KULLING 1934, SANDFORD 1950 and 1956) though large areas have yet to be investigated in detail.

In the south BIRKENMAJER (1958 and 1959) described a succession matching

Table V

South (1)	North-west (2)	North-east (2)
(49) 584 ± 25	(53) 541 ± 24	(19) 537 ± 31
(50) 556 ± 24		
	(60) 529 ± 15	(20) 618 ± 11
		(21) 636 ± 20
		(22) 581 ± 19

Determinations (51) 1939 ± 121, (70) 780 ± 50, (71) 813 ± 54, (72) 1430 ± 8, (73) 1393 ± 14 m. y. from the north-west have been discussed on p. 18 under Pyroxenes where it was concluded that the results could well be unreliable and were not capable of indicating the true age of the crystallization of the eclogites.

most of the north-central area but with several minor breaks. This area is part of the west coast belt which was subjected to Tertiary diastrophism (ORVIN 1940). In the north-west it seems that only Lower Hecla Hoek rocks are exposed (HARLAND 1960 b, and GEE and HJELLE 1966).

We first consider the hypothesis that, with minor modifications due to Caledonian overprinting, the apparent ages represent an event of early Cambrian or late Pre-Cambrian age. Although Middle and Upper Cambrian fossils have not been found, the apparently continuous carbonate facies in the north-centre and south-west would almost certainly preclude the possibility of a Lower or Middle Cambrian age for a metamorphic event. Moreover Lower Cambrian fossils are found at the base of this succession in north-centre, north-east and south. In these three areas Cambrian rocks are underlain respectively by the Polarisbreen Series (HARLAND and WILSON 1956), the Sveanor formation (KULLING 1934) and the Gåshamna series (BIRKENMAJER 1958). These formations represent a clastic interlude between thick fine grained carbonate sequences. There seems little doubt about their correlation and the first two at least are boulder-bearing and have been interpreted as tillites of the latest Pre-Cambrian, Varangian, glaciation (WILSON and HARLAND 1964). This stratigraphical unit is the only one to which metamorphism involving some disturbance could be fitted if it took place within say 100 m. y. either way. In support of such a correlation we mention, in addition to the evidence of clastic sedimentation, the greater thickness of Comfortlessbreen schists (WILSON and HARLAND 1964 p. 212—4) and the volcanic and hypabyssal boulders in the Sveanor formation *(op. cit.* p. 211—2) and which KULLING (1934) argued could have resulted from a pre-Sveanor volcanic episode. Both these characteristics would appear to be extremely local and could relate to localized geanticlinal activity in the north-east and north-west which did not affect the neighbouring areas of deposition. KLITIN (1960) suggested a non-glacial explanation, the boulder beds being accounted for by instability in the hinge region of the geosyncline. This view was put forward without local evidence, and the "hinge" was taken from a reconstruction by HARLAND (1959) which may well be modified in the light of recent work including that reported in this paper. We accept a glacial explanation for these boulder beds but consider in addition the possibilty of associated tectonic and/or igneous events.

Against this correlation we comment that:

(i) over a wide area in Spitsbergen and also in east Greenland and north Norway there is a similar succession in this part of the stratigraphic column which argues against any major diastrophism;

(ii) a careful study of the boulders in Ny Friesland shows that, apart from many crystalline exotics not yet known in Spitsbergen, most boulders have been matched in detail with the underlying succession but not deeper than 300 m below the base of the Polarisbreen Series (WILSON and HARLAND 1964). This suggests that even in areas of erosion no great uplift took place — the crystalline rocks being interpreted as far-travelled;

(iii) although the north-west rocks are 90 km from the nearest recorded Upper and Middle Hecla Hoek, the other two areas are within 5 or 10 km at the present time of the Sveanor formation or the Gåshamna series (compare Fig. 1, and map in WILSON and HARLAND 1964).

A second explanation requires more marked Caledonian overprinting on rocks metamorphosed still earlier. The rocks in the north-west and south are thought to be part of the Lower Hecla Hoek succession (HARLAND 1960 b, BIRKENMAJER 1958, 1960 and GEE and HJELLE 1966) so that another tectonic episode within, say, the upper Lower or Middle Hecla Hoek might be postulated. In support of this hypothesis it may be noted that HARLAND (1960 b) suggested the development of a geanticline in Lower Middle Hecla Hoek time between the north-centre and the south and west. The north-west could well have been part of this. The same evidence used to support the geanticline, namely the greater variation in Hecla Hoek facies about this time, may be used to support our second hypothesis. The major break in the south, followed by the Slyngfjellet conglomerate, could accommodate this alternative. There is certainly more stratigraphical scope at that time for a general disturbance and we have no reason to exclude the north-east from this, especially if the volcanic facies of the Kap Hansteen formation (KULLING 1934) be taken into account.

The third hypothesis to consider is the one advanced by HAMILTON and SANDFORD (1964) that the rocks in question are pre-Hecla Hoek (i.e. the "Archaean" of SANDFORD 1950) overprinted by Caledonian metamorphism. This could only apply to the north-east samples acording to our stratigraphical correlations, but we are not disposed to make an exceptional explanation of them along these lines, for pre-Hecla Hoek rocks have not yet been unambiguously demonstrated in Spitsbergen. An estimate of the length of time occupied by Hecla Hoek sedimentation suggests that any pre-Hecla Hoek basement would probably exceed an age of 900 m. y. (cf. HARLAND 1961, p. 116). If we are wrong in ignoring the high pyroxene ages (51), (70), (71), (72), (73) and thus also wrong in our correlation then there is also support for this hypothesis in the north-west.

We conclude that the five rocks under consideration have very important implications. In the north-west there is no stratigraphical objection to the two first mentioned hypotheses. The third hypothesis could apply to the north-east and to the eclogite bearing rocks of the north-west but we do not favour this interpretation. We feel the radiometric evidence favours hypothesis 1, but the strati-

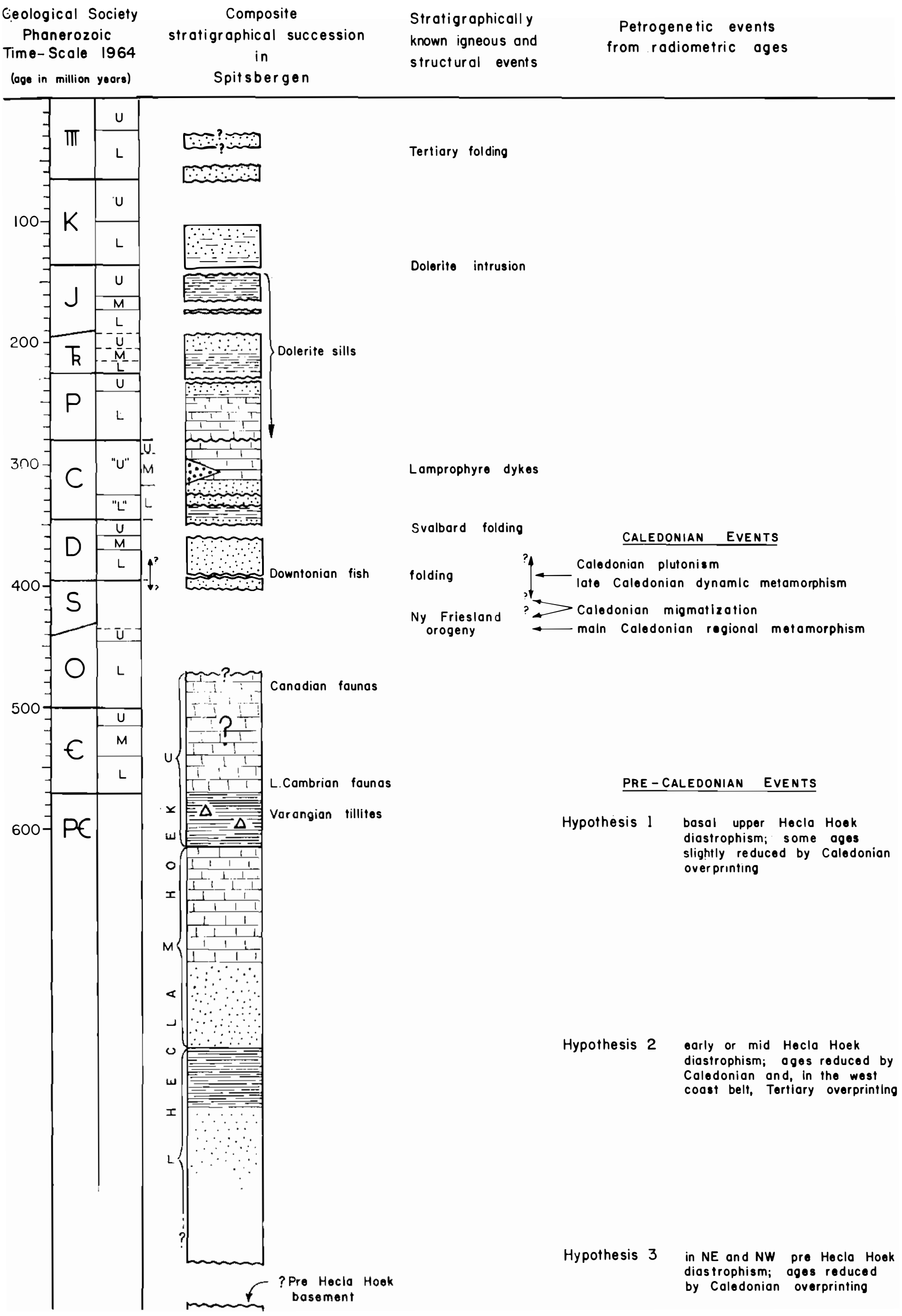


Fig. 4. Stratigraphical scheme to summarize possible correlations of petrogenetic events considered in this paper.

graphic evidence favours hypothesis 2. Hypothesis 1 would be easier to accept if some thermal event could have affected rocks at depth while submarine sedimentation at the surface was only slightly disturbed. Clearly more data are needed and we plan to continue this investigation.

North Atlantic Caledonian province

Close comparisons on geological grounds have long been made between East Greenland, Scotland, Scandinavia and Spitsbergen, by Bailey and Holtedahl (1938) and recently by Harland (1961, 1965). Radiometric determinations from the four areas strengthen these comparisons especially with regard to the succession of Caledonian events:

Post-tectonic granite intrusion is a marked feature of all four areas, yet though the areas are now widely separated in space this phase is very restricted in time at c. 390—400 ± 20 m. y., approximately the Silurian—Devonian boundary, and the lower part of the Devonian.

The main Caledonian tectogenic event is also highly localized in time at c. 425 ± 10 m. y., though later stages last until 400 m. y. The Dalradian metamorphism (Scotland) of c. 470—440 m. y. has not been found elsewhere.

Apparent ages which suggest the occurrence of a late Pre-Cambrian event occur in Scandinavia at c. 600 m. y., in Spitsbergen at c. 600 m. y., and in Scotland at c. 740 m. y. In north East Greenland no representative ages have been obtained for the postulated Pre-Cambrian Carolinidian folding, although an apparent age of 545 m. y. has been obtained from North Ellesmere Island, and a single 490 m. y. result from the "Caledonian" belt of East Greenland.

In Scotland, East Greenland and Scandinavia, where the Caledonian belts are known to be marginal to Pre-Cambrian rocks, appropriate ages have been found:

Scotland: Scourian c. 2460 m. y., Laxfordian c. 1600—1000 m. y.
East Greenland 2290—1600 m. y.
Baltic Shield: from Katachean, 3500—3000 m. y. to late Telemark, 1130—900 m. y.

In Spitsbergen no Archaean has been clearly established, and no supporting radiometric evidence is available.

The summary above is based on the following references:

East Greenland	Haller and Kulp 1962 Wager and Hamilton 1964
Scotland	Gilletti *et al.* 1961 Miller and Brown 1965
Scandinavia	Magnusson 1960 Polkanov and Gerling 1960 Neumann 1960 Broch 1964

Summary of conclusions

1. Radiometric evidence gives an age for the Isfjorden Dolerites of ca. 150 m. y. which is in close agreement with the stratigraphical relations and indicates a late Jurassic or early Cretaceous age.
2. Previously unrecorded monchiquite dykes give an apparent age of 309 ± 5 m. y. apparently being intruded during the Middle Carboniferous.
3. Radiometric evidence for the age of the base of the Devonian in Spitsbergen is found to be indecisive, but the geological relations are such that they should be capable of providing suitable radiometric data for a critical lower limit.
4. The main Caledonian crystallization event throughout northern Svalbard appears to have occurred at c. 430—420 m. y. and possibly lasted until c. 400 m. y. producing local effects. Final post-crystalline deformation could have taken place at 380 ± 10 m. y. Very extensive post-tectonic granite intrusion took place at c. 400 ± 20 m. y.
5. A limited number of Pre-Cambrian apparent ages have been obtained. Three explanations for these ages at 580 ± 60 m. y. are suggested.
   Metamorphism at c. 600 m.y. (apparent ages affected by Caledonian overprinting).
   Metamorphism at c. 700—800 m. y. (strongly affected by Caledonian overprinting).
   Archaean metamorphism pre-900 m. y. (with greater overprinting, following HAMILTON and SANDFORD (1964)).
6. Earlier Pre-Cambrian apparent ages from clinopyroxenes from eclogites have not been accepted.
7. The Caledonian events occurred at a similar time and in similar order to those of East Greenland, Scandinavia and Scotland.
8. Future work in Spitsbergen could provide critical radiometric data: on early (pre-500 m. y.) events, and for the base of the Devonian.

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