K–Ar AGES FOR THE TERTIARY OF EAST GREENLAND

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K-Ar whole-rock ages of extrusive rocks from the Tertiary of East Greenland show variable argon loss but the oldest ages of 55–60 m.y. are similar to those found for basalt plateaux elsewhere in the North Atlantic Tertiary province. The pattern of ages from samples collected serially in a vertical traverse of a single flow is discussed. Minerals separated from intrusive rocks show the effects of slow cooling and different retentivities for radiogenic ^{40}Ar with biotites giving generally younger ages than amphiboles. The later give ages clustering around 50 m.y. which is marginally younger than ages for Tertiary instrusions in the British Isles and West Greenland. The long cooling history recorded in the biotite ages is consistent with evidence for deep burial found in the lowest basalts.

Tertiary igneous rocks outcrop over considerable areas in East Greenland between Angmagssalik (lat. 66°) and Scoresbysund (lat. 70°), while more scattered occurrences are found as far north as Shannon Ø (lat. 75°). A useful description of these rocks and the associated sediments has been given by Wenk (1961) and a sketch map showing the approximate extent of the Tertiary formations is given in fig. 1. Further occurrences south of Angmagssalik have recently been reported by Bridgwater & Gormsen (1969). They belong to the North Atlantic Tertiary province and have long been assumed on petrological and palaeontological grounds to be essentially contemporaneous with similar igneous rocks in West Greenland, East Canada, Iceland, the Faeroes and the British Isles (Holmes, 1918).

Interest in this province has recently received considerable stimulus from the hypothesis of ocean-floor spreading (Vine, 1966). However, the relationship, if any, between volcanic activity which commenced in the North Atlantic in the Paleocene-Eocene, and the opening of the Atlantic Ocean which appears to have begun considerably earlier is not fully understood at the present time.

A number of radiometric ages have been published for rocks from Lundy (Miller & Fitch, 1962; Dodson & Long, 1962), Arran (Miller & Harland, 1963), Skye (Long, 1964; Moorbath & Bell, 1965), Iceland (McDougall & Wensink, 1966; Gale et al., 1966; Moorbath & Walker, 1965; Moorbath et al., 1968), St. Kilda and Rockall (Miller & Mohr, 1965), the Sithean Sluagh plug, L. Fyne (Miller & Brown, 1965), Ardnamurchan (Miller &

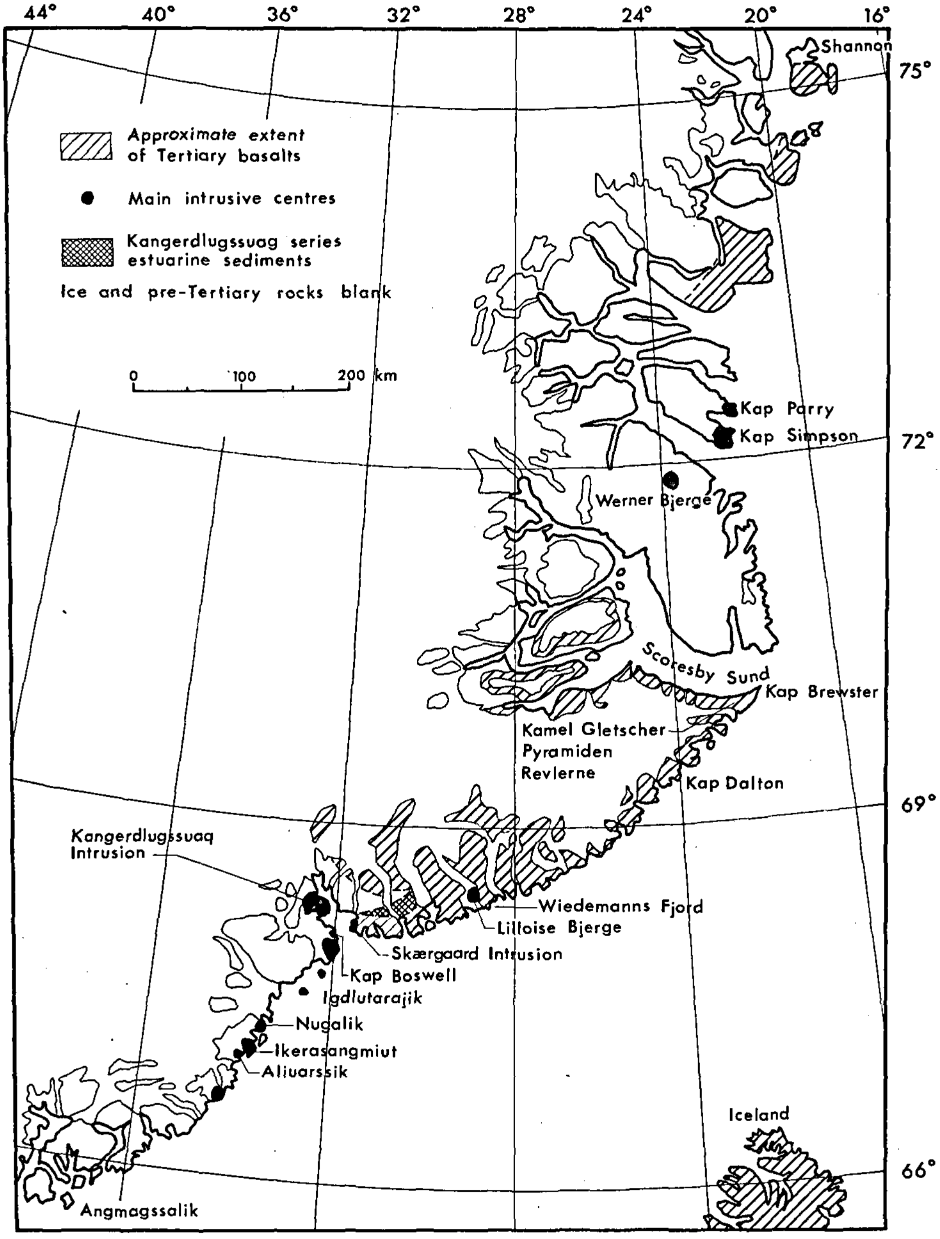

Fig. 1. Sketch map showing approximate distribution of Tertiary rocks in East Greenland and the localities of the specimens analysed in this work.

Brown, 1965), Ailsa Craig (Hamilton, 1966), Mull (Miller & Brown, 1965), the Mountains of Mourne (Miller & Brown, 1963) and the Faeroes (Tarling & Gale, 1968). These results and many unpublished data of one of the authors (R.D.B.) confirm in general the Paleocene-Eocene age (i.e. 65–40 m.y.) of these rocks indicated by some, but not all, interpretations of the palaeontological evidence. In Iceland, however, no ages older that 16 m.y. were found.

With the exception of Rb-Sr ages for the Kangerdlugssuaq intrusion and a contact metamorphosed gneiss from Kræmers Ø (Hamilton, 1966) no radiometric ages for the East Greenland Tertiary have been published. The object of this study was to verify these results and clarify the conflicting interpretations of palaeontological evidence. Palaeomagnetic measurements on some of the lavas studied have already been reported (Tarling, 1967).

Geology

The samples studied come, with one exception, from the area between Angmagssalik and Scoresbysund which has been described geologically by Wager (1934, 1947). The other sample comes from the Werner Bjerge complex (Bearth, 1959) just north of Scoresbysund.

Igneous activity in this region commenced with series of basalts and pyroclastics, probably sub-aqueous, deposited on a thin sequence of estuarine sediments yielding a fauna of Senonian or very early Tertiary age (Wager, 1934). Outpourings of tholeiitic lava then built up an extensive plateau which may be as much as 7 km thick. Sediments occur near the top of this succesion of Kap Dalton (Wager, 1935) and Kap Brewster (Hassan, 1953). Two series of sediments are recognized: the older being variously placed in the Lower to Middle Eocene (Ravn, 1933), Upper Eocene to Oligocene (Hassan, 1953) or Miocene (Sorgenfrei, 1940) the younger being regarded as probably Miocene (Hassan, 1953).

The plateau basalts were succeeded by central-type volcanic activity of a more alkaline nature (Anwar, 1955) and a number of large basic plutons (of which the best known is that at Skaergaard) were intruded into the base of the basalt succession. Subsequently the basalts suffered monoclinal flexuring accompanied by the injection of an intense dyke svarm. Activity ceased with the intrusion of granites and syenites, and possibly small carbonatites (Bridgwater & Gormsen, 1969).

Analytical methods

Both potassium and argon were determined using the Institute of Geological Science's equipment at Oxford under the auspices of Dr. N.J. Snelling. Potassium contents were determined by replicate flame photometric analysis with a Baird-Atomic KY3 photometer and an internal lithium standard for dissolved aliquots of the minerals and an »EEL« photometer for dissolved aliquots of the basalt »whole-rocks«. The accuracy and reproducibility attainable with the EEL photometer has been discussed by Baker et al. (1967) who concluded that the accuracy in the range 0.1–10 % K with this instrument is within ± 1.5 %. Unpublished data for the international standards Wl and Bern 4M obtained by one of us (Beckinsale) indicate that the Baird-Atom c photometer is less prone to interference effects than the EEL instrument and that this author's potassium values are within ± 1 % of the accepted values over the range 0.5–9 % K.

Radiogenic ^{40}Ar was determined by isotope dilution using an A.E.I. MS 10 mass spectrometer and an enriched ^{38}Ar »spike«, exponentially diminishing volumes of which were pipetted into the argon extraction system. About every tenth spike aliquoet was calibrated against a known volume of H_2O and CO_2-free air and the intervening volumes interpolated by a least squares procedure using a computor. Results for the standards P 207 (Lanphere & Dalrymple, 1965) and Bern 4M (Beckinsale, unpublished data) suggest that the argon analyses are within ± 3 % of the mean values obtained internationally.

The measured or adopted values for the parameters used in the calculation of ages from the raw data were as follows:

$^{40}K/K$	1.18×10^{-2} atom percent
total	5.480×10^{-10} yr^{-1}
argon	0.575×10^{-10} yr^{-1}

The decay constants used are based on a collation of recent physical data which is fully discussed by Beckinsale & Gale (1969). It is important to note that these decay constants yield ages about 1 m.y. older at 60 m.y. than those calculated using the decay constants recommended by Smith (1964) which have been generally adopted in the past.

Analytical errors are quoted at the 66 % confidence level and have been computed on the basis of the theory developed by Gale (Baker et al., 1967) suitably modified explictly to static argon analyses.

Discussion of results

The results are given in table 1, see pp. 32–33.

Basalt whole-rock ages

Out of the large collection of basalts brought back by the Oxford University East Greenland Expedition in 1965 (Fawcett et al., 1966) only a few specimens were found to be free of glass, altered glass, or extensive alteration products. Dating such glassy, devitrified or altered material was not considered worthwhile (Webb & McDougall, 1967), and consequently it has not been possible to evaluate directly the palaeontological evidence from Kap Brewster and Kap Dalton, since faults of unknown displacement separate the fossiliferous sediments from the main basalt areas where suitable samples were found. However, both the dated basalts and the sediments are believed to represent very nearly the top of the pile (Wager, 1935; Hassan, 1953; Fawcett et al., 1966) and should be of very similar age. The basalts show a pattern of radiogenic argon giving a spectrum of ages from ca. 60 m.y. to ca. 45 m.y. (except for one anomalous value of 33 m.y.). The oldest ages fall in the range 55–60 m.y. and this is regarded as a close approach to the true age of these rocks. According to Funnel's (1964) Tertiary time scale this places them in the Paleocene. No results have been obtained for the lower lavas because all available specimens were considered unsuitable.

In a vertical traverse of one flow (samples nos EG 7147–48–49–50–51) the fine-grained upper and lower contacts gave 58 ± 3 m.y. (average of two argon determinations) and 56 ± 2 m.y. which are likely to be good approximations to the true age (and are not significantly different from the oldest ages obtained). Samples from the interior of the flow which is about 30 m thick gave ages down to ca. 46 m.y. and appear to have suffered argon loss in the same pattern as has been found for the Palisades sill (Erickson & Kulp, 1961). In thin sections of the basalt this pattern can be seen to correlate with increasing deuteric alteration and large quantities of brown glass, now partially altered, which probably contains the bulk of the potassium in the rock. A study of the degree of oxidation and the palaeomagnetic properties across a single Icelandic basalt (Watkins & Haggerty, 1967) showed patterns similar in form to the age pattern reported here, which were correlated with its thermal history. The limited data presented here reinforce Erickson & Kulps' suggestion that substantial improvements in the accuracy of K-Ar ages would result from selecting for analysis only the chilled margins of basic rock bodies.

Ages of intrusive rocks

The remaining ages all pertain to rocks representing the closing stages of igneous activity in the area. The age of 50.4 ± 1.2 m.y. for a biotite from the Kangerdlugssuaq intrusion is in accord with an Rb-Sr mineral isochron age of 49 ± 2 m.y. reported by Hamilton (1966). The amphibole ages from

Table 1. K-Ar ages of rocks and minerals from East Greenland

Sample number:	Description and reference:	K % (Mean)	No. of K determinations:	Std. dev.:	^{40}Ar radiogenic (%):	^{40}Ar rad (cm^3/gm stp x 10^{-8})	Std. dev. (x10^{-8})	Age (m.y.)	Mesh sizes:
1. Basalts (Fawcett et al., 1966)									
EG 7124	Pyramiden	0.237	3	0.001	73.00	44.79	1.413	47.6±1.5	−20+80
7126	Pyramiden	0.166	3	0.002	31.92	21.94	2.025	33.4±3.1	−40+80
7127	Pyramiden	0.175	3	0.002	59.17	37.72	1.475	54.1±2.2	−40+80
7131	Pyramiden	0.125	3	0.003	40.75	21.84	1.419	44.0±3.1	−20+80
7139	Revlerne	0.308	3	0.002	69.99	63.20	1.975	51.6±1.6	−40+80
7147	Kap Brewster*)	0.190	3	0.002	49.51	41.98	2.381	55.4±3.1	−40+80
–	Kap Brewster (Ar repeat)	–	–	–	50.05	45.60	2.135	60.1±2.8	
7148	Kap Brewster	0.221	3	0.002	69.17	40.09	1.310	45.7±1.5	−40+80
–	(Ar repeat)	–	–	–	70.41	40.95	1.405	46.7±1.6	
7149	Kap Brewster	0.185	4	0.004	66.98	33.71	1.201	45.9±1.8	−20+80
7150	Kap Brewster	0.184	5	0.002	60.38	42.37	1.580	57.8±2.2	−40+80
7151	Kap Brewster	0.241	3	0.002	80.49	53.75	1.513	56.1±1.6	−20+80
7168	Kamel Gletscher	0.206	3	0.003	63.58	45.00	1.614	54.9±2.1	−20+80
7168	Kamel Gletscher	0.182	3	0.001	47.79	34.40	1.682	45.0±2.9	−20+80
7175	Kamel Gletscher	0.164	3	0.001	54.15	29.23	1.882	45.0±2.9	−20+80
–	(Ar repeat)	–	–	–	48.85	30.17	0.855	46.9±1.3	– –
2. Intrusives									
EG 7544	Alkali amphibole, syenitic breccia Aliurssik, (Brown 1968)	0.683	3	0.002	70.34	133.0	8.620	49.0±3.1	
–	biotite, ditto	6.969	3	0.065	75.63	1036	44.02	37.5±1.6	
7728	Biotite, quartz syenite Ikerasangmiut (Brown, 1968)	7.350	3	0.032	84.41	1111	27.22	38.1±1.0	

the Lilloise alkaline intrusion are not very different from this value, but biotite yielded an appreciably younger age in agreement with an unpublished Rb-Sr biotite – W. R. intersection age (by Brooks) of 38 ± 3 m.y. This Rb-Sr age is in effect a biotite age and allows no doubt that these biotites are recording a real event. Clearly, as is well known (Hart et al., 1968) biotite became a closed system to ^{87}Sr and ^{40}Ar at a later date and lower temperature than those at which amphibole became a closed system to ^{40}Ar. Similar discordance is shown by amphibole and biotite from plutons in the Kialineq area (samples EG 7544 and 7728). Unfortunately only

Sample number:	Description and reference:	K % (Mean)	No. of K determinations:	Std. dev.:	^{40}Ar radiogenic (%):	^{40}Ar rad (cm^3/gm stp x 10^{-8})	Std. dev. (x10^{-8})	Age (m.y.)	Mesh sizes:
736	Alkaliamphibole, quartz syenite, Kap Boswell (Wager, 1934)	0.628	4	0.006	50.00	129.5	9.802	51.8 ± 3.9	
4583	Biotite, pulaskite Kangerdlugssuaq (Wager, 1965)	7.788	2	0.022	85.32	1560	37.21	50.4 ± 1.2	
7058	Alkali amphibole, syenite, Lilloise Bjerge (Wager, 1934)	1.230	5	0.017	85.60	240.6	8.033	49.2 – 1.8	
7059	Alkali amphibole, ditto	1.502	4	0.011	82.10	269.5	9.260	45.2 – 1.6	
7062	Biotite, syenitic breccia, ditto	7.714	3	0.014	84.07	1254	30.67	40.8 – 1.0	
7026	Kaersutitic amphibole, lamprophyre dyke, Wiedemanns Fjord	0.953	3	0.004	83.38	197.8	4.906	52.2 – 1.3	
WW 104	Biotite, syenite, Werner Bjerge (Bearth, 1959)	7.320	6	0.099	45.74	831.0	57.35	28.7 – 2.0	

*) EG 7147 to EG 7171 from one flow, with approximate heights from base as follows:
EG 7147: 10 cm
EG 7148: 7.5 m
EG 7149: 15 m
EG 7150: 24 m
EG 7171: 30 m (about 1 m below scoriaceous top zone).

biotite was available from the Werner Bjerge plutonic complex and this gave an unexpectedly low age of 28.7 ± 2.0 m.y. The cooling history of the Tertiary plutons in East Greenland was probably protracted because of their deep burial under the basalt succession, the lowest members of which show evidence of low grade metamorphism also attributed to burial (Wager, 1934). There is no proof that the amphiboles do not contain excess argon, but it is thought highly unlikely that in such widely separated localities as the Lilloise Bjerge and the Kialineq area amphiboles with different potassium contents could incorporate on crystallization just the right amount of argon to yield such similar ages today. Making apparently reasonable assumptions for the relative temperatures of closure of biotite and amphibole to argon it is concluded that the average rate of cooling of these plutons was of the order of only 40°C $m.y.^{-1}$.

Thus while the biotite ages do not give the time of intrusion, the amphiboles may give a close approach to it, yielding an average age of 49 ± 2 m.y. This is essentially in agreement with published data for many Tertiary intrusives in the British Isles and with ages for the Sarqata Qaqa pluton in West Greenland (R.D.B., unpublished data). However, in detail both the British and West Greenland intrusives yield slightly older ages (55 m.y.) than those in East Greenland.

Conclusions

The results of this study indicate that the latest plateau basalts in East Greenland were extruded in Paleocene times (55–60 m.y.) and with present techniques are indistinguishable in age from the Faeroes basalts (Tarling & Gale, 1968). A recent comparison of the palaeomagnetic properties of these East Greenland lavas with the so called »trap diabases« of S.W. Greenland (Tarling, 1967) which are now known to be at least 160 m.y. old (Larsen & Møller, 1968) is therefore invalid. In combination with the stratigraphic evidence our results show that the extrusion of this immense volume of lava was confined to the Paleocene. Ages on separated amphiboles show that the latest intrusive event occurred about 50 m.y. ago or in the Lower Eocene. The entire history of igneous activity in East Greenland lasted, therefore, only about 15 m.y., and any attempt to date events within this period would be difficult in the absence of very suitable material.

It is now established that basalts of 55–60 m.y. age occur on both sides of the Atlantic more or less symmetrically disposed with respect to the Mid-Atlantic Ridge, while progressively younger rocks are encountered on approaching the central rift zone in Iceland which is still active. However, palaeomagnetic and other evidence that the opening of the Atlantic Ocean began in the Mesozoic appears incontrovertible. Thus our final conclusion is that any relationship between the forces responsible for ocean floor spreading and the mantle event responsible for the major Paleocene-Eocene igneous and hydrothermal (Darnley et al., 1965) activity remains to be elucidated.

Added in proof

A biotite from a carbonatite dyke of supposed Tertiary age collected by Bridgwater and Gormsen (1969) from the area of Umivik south of Angmagssalik and referred to on p. 27 and p. 29 has given a K-Ar age of 1678 m.y.

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Dansk sammendrag

Aldersbestemmelser ved K-Ar metoden af tertiære extrusive bjergarter fra Østgrønland viser, at varierende tab af argon med den ældste datering på 55–60 mill. år er af samme størrelsesorden som aldersbestemmelsen for plateaubasalt i andre områder af den nordatlantiske tertiære basaltprovins. Der er foretaget en vurdering af variationen af aldre fra prøver samlet i forskellige højder fra en enkelt lavastrøm. Variationen tyder på, at centret i mindre grad har tilbageholdt radiogent ^{40}Ar end de marginale dele, hvis aldersbestemmelser man antager at ligge ret nær den virkelige alder.

Mineraler, der er separeret fra intrusive bjergarter, viser betydningen af en langsom afkøling. Biotiten og amphibolen tilbageholder i en forskellig grad radiogent ^{40}Ar, således at biotiten generelt giver yngre aldersbestemmelser end amphibolen. Aldersbestemmelser af det sidstnævnte mineral ligger omkring 50 mill. år, hvilket er lidt mindre end aldrene for tertiære intrusioner på De britiske Øer og i Vestgrønland. Den lange afkølingsperiode, som er påvist i biotit, er i overensstemmelse med petrografisk evidens for dyb beliggenhed af de nederste lava-horisonter.

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