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DE DANSKE EKSPEDITIONER TIL ØSTGRØNLAND 1947–58
Under Ledelse af Lauge Koch

ABSOLUTE AGE DETERMINATIONS IN EAST GREENLAND

BY

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WITH 19 FIGURES IN THE TEXT
AND 4 PLATES

KØBENHAVN
C. A. REITZELS FORLAG
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PREFACE

In the autumn of 1957 Professor J. L. Kulp of the Lamont Laboratory, Columbia University, New York, applied to me, offering me close co-operation on extremely favourable conditions for the purpose of making absolute age determinations in East Greenland. For several years we had been contemplating to start such investigations, and the name of Professor Kulp was so well-known in scientific circles that I was greatly pleased to accept his offer.

At that time I took it for granted that my activities in East Greenland were to continue for the next four years, also, and it was therefore agreed that samples should be collected in close co-operation between an assistant of Professor Kulp and the geologists of my expedition. It was further planned that the samples taken during the first year should be provisionally examined, and if it turned out desirable to secure additional material from the localities first investigated, they might be visited again. It was our hopes to establish a teamwork of geophysicists and geologists in intimate co-operation, in order that samples yielding doubtful results might be replaced by fresh samples if desired.

At the great disappointment of my co-operators and myself, howewer, my expeditions were brought to and end before the projected co-operation could be established. But during a visit to Basel, Professor Kulp took out a number of samples, which he afterwards examined for us free of charge, for which courtesy I wish to express to him my sincere gratitude.

It will appear from the present paper that his studies have yielded great and significant results. Provided that the planned collecting during four years had been carried out, it would probably have been possible to determine the age of the two large pre-Cambrian sedimentary series termed the Thule group and the Eleonore Bay group, as well as the age of the pre-Cambrian fold-mountain range present in Northeast Greenland, a continuation of which possibly occurs along the north coast of Ellesmere Island. Owing to the cessation of the expeditions, however, this aim was not attained, but I am greatly indebted to Professor Kulp for the important results he has arrived at on the basis of the material available to him.

Lauge Koch

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INTRODUCTION

With the rapid development of the isotopic methods of age determination it is now possible to reconstruct the absolute chronology of areas of complex metamorphic and orogenic history. These methods are elaborate and expensive but of definitive value in such areas. The application of these methods to the East Greenland province is particularly inviting since prolonged geologic studies of high quality provide a sound base of information to which the isotopic ages can be related. The geologic events range in time for an old basement of unknown age through two subsequent geosynclines of Precambrian age, early Paleozoic deposition, great Caledonian orogeny, Devonian and Permian igneous activity and Tertiary volcanism.

The unsurpassed exposures permit accurate definition of the relative ages of the geologic events, but in order to understand the total history, the rates of geologic processes and their extent, absolute ages are required.

This report presents a preliminary study of the absolute ages of the rocks of Eastern Greenland conducted in cooperation between the Geochemistry Laboratory of Columbia University and the East Greenland Expeditions directed by Lauge Koch. The available samples were stored at the University of Basle. These were either hand specimens or chips as they had been collected for petrographic rather than isotopic age studies. As a result only a preliminary survey was possible using the *potassium-argon method* (Carr and Kulp, 1957). The uranium-lead method on zircon will be of great use in future studies but this requires large samples. The most critical samples were selected in a conference of the authors at Basle. The isotopic ages were determined under the direction of J. L. Kulp by R. Kologrivov at Columbia University. J. Haller provided the petrographic descriptions of the samples and the petrologic discussion of the data and its implications for the structural history of the East Greenland Fold Belt.

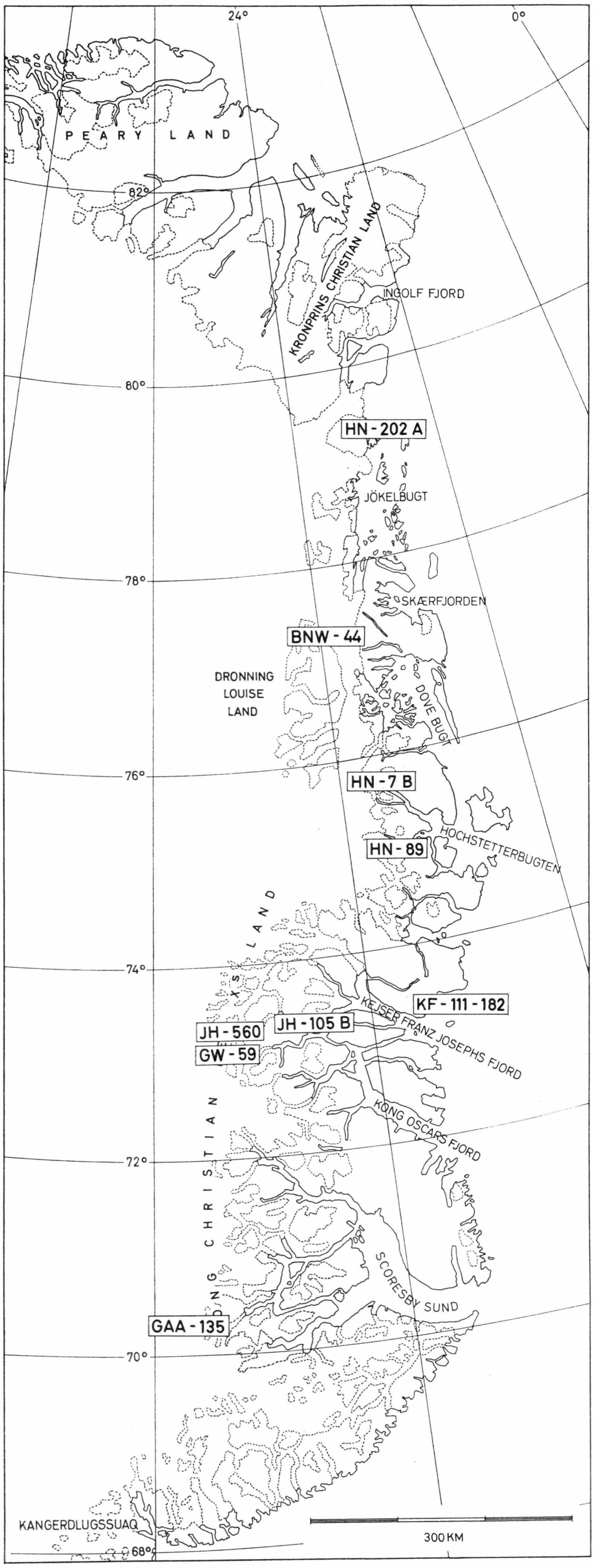


Fig. 1. Sample locations.

LOCATION AND SAMPLES

The general area of concern in this investigation and the location of the samples are shown in Figure 1. The petrographic description of the individual samples follows:

Sample GAA-135 (Coll. P. Stern, 1958)

Locality:	*Paul Stern Land*, northern edge of Vestfjord Gletscher (70°20′ N, 29°47′ W). Block on superglacial drift from adjacent bed-rock.
Geological Setting:	Autochthonous Precambrian basement complex, nonconformably overlain by basal strata of the Eleonore Bay Group (Precambrian geosynclinal sediments), western frontland of the Caledonian belt.
Petrography:	Rather massive variety of *biotite-albite-microcline-alkali-granite*, bearing apatite, ore, garnet and carbonate.
Reference:	Wenk (1961 b) pp. 17–22, pls. IV a, V, VI, IX.

Sample HN-89 (Coll. J. Haller, 1956)

Locality:	*C. H. Ostenfelds Land* (75°00′ N, 21°50′ W) Maagenæs, Grandjeans Fjord.
Geological Setting:	Polymetamorphic migmatite which originally had been a part of the Precambrian basement. The complex represented by Sample HN-89 was subjected to the principal Caledonian regional metamorphism and, in addition, to a second metamorphism during a late orogenic spasm.
Petrography:	Mesocratic, gneissose *biotite-perthite-oligoclase-granodiorite*, bearing epidote, apatite, titanite, ore.
References:	Haller (1956 a), p. 20; (1957) pp. 18–21.

Sample BNW-44 (Coll. J. Haller, 1955)

Locality:	*Dronning Louise Land*, erratic boulder from Britannia Sø (77°10′ N, 24°00′ W). The sample probably derives from northern Dronning Louise Land.
Geological Setting:	Sample BNW-44 was supposed to represent a Precambrian eruptive (Thulean eruptive).
Petrography:	Medium-grained *plagioclase-quartz-hornblendite*, bearing biotite, calcite, epidote and apatite.
Reference:	Peacock (1958 a), pp. 91–113.

Sample GW-59 (Coll. E. Wenk, 1951)

Locality: Western *Fraenkels Land* (73°10′ N, 28°30′ W). East flank of Trappebjerg, 2,090 m altitude.

Geological Setting: Precambrian sediment being a part of the Caledonian superstructure. Phyllitic layer from the "Shoulder Series", which is the uppermost bed group of the Lower Eleonore Bay Group in the Nunatakker Region of Central East Greenland.

Petrography: *Phyllite.*

References: Wenk and Haller (1953), p. 18, fig. 13, pl. I; Haller (1956 c), pp. 40–44, pls. I, II.

Sample JH-560 (Coll. J. Haller, 1951)

Locality: Western *Fraenkels Land* (73°11′ N, 28°35′ W), South slope of Mount Kerberus, 2,200 m altitude.

Geological Setting: Precambrian sediment being a part of the Caledonian superstructure. Sample JH-560 represents the black shaly basal bed of the "Synclinal Series" of the Upper Eleonore Bay Group in the Nunatakker Region of Central East Greenland.

Petrography: *Phyllitic layer* from black sandy shale to quartzitic slate.

References: Wenk and Haller (1953), p. 18, figs. 8, 13, pl. I; Haller (1956 c) pp. 50–54, fig. 21, pls. I, II.

Sample JH-105 B (Coll. J. Haller, 1949)

Locality: Western *Andrées Land* (73°20′ N, 26°35′ W). South side of Jomsborg, Renbugten, Isfjord.

Geological Setting: Caledonian metamorphite of probably sedimentary origin. Sample JH-105 B represents a band of mica-hornblende-schist which is involved in the main orogenic infrastructure ("Migmatite Dome Nigglis Spids").

Petrography: *Phlogopite-rich lenticle* of phlogopite-diopside-hornblende-schists.

Reference: Haller (1953), pp. 69–73, figs. 14, 23.

Sample HN-202 A (Coll. J. Haller, 1958)

Locality: *Lambert Land*, mouth of Jomfru Tidsfordrivs Fjord, (79°20′ N, 19°40′ W).

Geological Setting: Caledonian pegmatite which represents a late-tectonic intrusive of the main orogeny. The pegmatite intruded along shear planes into biotite-schists.

Petrography: *Biotite-oligoclase-pegmatite*, bearing epidote-zoisite within the wisps of mica.

Reference: This paper.

Sample HN-7 B (Coll. J. Haller, 1955)

Locality: Head of *Bredefjord* (75°41′ N, 22°15′ W)

Geological Setting: Caledonian intrusive granite, which forms a post-tectonic stock within an additional young Caledonian thrust-fold belt.

Petrography: Coarse-grained *muscovite-oligoclase-microcline-granite*, being a pegmatoid variety of a two-mica-granite.

References: Haller (1956 a) pp. 20–21; Sommer (1957) pp. 22–23, Fig. 10.

Sample KF-111-180-182 (Coll. P. Graeter, 1950)

Locality: 2 km north of *Kap Franklin* (73°15′ N, 22°10′ W) at the mouth of Kejser Franz Josephs Fjord.

Geological Setting: Caledonian intrusive granite which intruded Middle Devonian clastics. The granite batholith and its sedimentary wall rocks are unconformably overlain by another Middle Devonian bed group.

Petrography: Homogeneous coarse-grained *two-mica-albite-perthite-alkali-granite*, bearing apatite, zircon, garnet, titanite, ore.

References: Bütler (1954) pp. 58–60, 70, 108, 116, pls. VI, IX; Graeter (1957) pp. 13–17, 37–38, 41, 96–98.

THE POTASSIUM-ARGON METHOD

The method of isotopic age measurement that was chosen for this study was that based on the decay of K^{40} to Ar^{40}. The decay constants are $\lambda_T = 5.303 \times 10^{-10}$ yr^{-1} and $\lambda_e = 0.583 \times 10^{-10}$ yr^{-1}.

The age relationship is:

$$T \text{ (age in million years)} = 0.1886 \ln \left(1 + \frac{Ar^{40}}{K^{40}} \frac{\lambda_T}{\lambda_e}\right).$$

Both the Ar^{40} and the K^{40} concentrations were determined by the method of isotope dilution. The experimental techniques have been described in detail by Long and Kulp (1962). These techniques permit the Ar^{40}/K^{40} ratio and hence the isotopic age to be determined to within $\pm 3\ ^0/_0$ or better.

For the isotopic age to be an absolute age, the mineral or rock must not have incorporated any pure Ar^{40} at the time of its formation and must have remained a closed chemical system. The first assumption has been found to be universally true for micas and generally true for rocks heated sufficiently for the phyllite grade of metamorphism to have developed. Thus for the separated micas, whole rock samples of phyllite and basalt in this investigation, no primary Ar^{40} should be present.

The assumption of a closed chemical system has been shown to hold true for mica and for most phyllites provided they have remained close to room temperature since their time of formation. Certain phases of basalt also appear to have this characteristic although certain other phases showed argon loss even at surface temperature up to $40\ ^0/_0$ (Erickson and Kulp, 1961). Thus in all cases the Ar^{40}/K^{40} ratio can be used to obtain an accurate and reliable minimum age.

If these minerals or rocks, however, have been heated to at least 150° C for long periods either by deep burial or by igneous or metamorphic processes, some argon will be lost from the system. If the heating is extensive, all of the argon will be lost even though the external form of the mineral or rock has been unchanged and the isotopic clock will begin again but now it will only date the last event, not the original time of mineral formation. These basic factors must be taken into account in interpreting the isotopic ages. In general, therefore, the isotopic age cannot be taken as the absolute time of a geologic event unless supporting data, usually in the form of multiple analyses in different minerals, is available. In the case of the K-Ar method, however, real minimum ages can be obtained and for many purposes these are adequately diagnostic.

ANALYTICAL DATA

Each of the samples subjected to analysis in this study were either separated micas or whole rocks. The results are given in Table 1.

Table 1. Results of K^{40}-Ar^{40} Measurements on Samples from East Greenland[1]).

Sample	*% K*	*Ar^{40*} scc/g*	*Isotopic Age (m.y.)*
GW-59 Whole Rock Phyllite	4.23	7.74×10^{-5}	412
JH-105 B Phlogopite	7.95	1.44×10^{-4}	402
GAA-135 Biotite	6.74	6.98×10^{-4}	1890
BNW-44 Whole Rock Quartz-dolerite	0.48	7.93×10^{-6}	376
KF-111-180-182 Biotite + Muscovite	7.87	1.37×10^{-4}	393
JH-560 Whole Rock Phyllite	5.02	9.53×10^{-5}	425
HN-89 Biotite	4.80	1.07×10^{-4}	490
HN-202 A Biotite	5.14	9.34×10^{-5}	405
HN-7 b Muscovite	8.99	1.57×10^{-4}	394

[1]) For additional results see Postscript.

DISCUSSION OF RESULTS

The structural evolution of North and East Greenland may be subdivided into five periods. These are unequal in their duration and show a great variety in character of crustal movements. They provide the outline for the discussion and are defined as follows:

1. The formation of the Precambrian basement complexes, usually called "*Greenland Shield*".

2. The building of a late Precambrian mountain chain (*Carolinides*) in Northeast Greenland. (This followed the deposition of the Precambrian Thule Group).

3. The emplacement of *Paleozoic fold belts* in North and Northeast Greenland. Possibly related to the Caledonian of the east shore of the Atlantic in Europe.

4. The post-Caledonian block faulting along the east coast.

5. Cenozoic disturbances.

An outline-map showing the principal structural provinces is presented on page 17.

The isotopic ages will be discussed in the relevant structural period. For convenience, the ages are grouped in this way in Table 2. The Paleozoic ages are rounded off to the nearest 5 m.y. and the old basement age to the nearest 50 m.y. consistent with the analytical errors. Also given are the rock and mineral type.

Table 2. Isotopic Ages Grouped by Structural Period.

Sample No.	*Rock Type*	*Mineral*	*Isotopic Age (m.y.)*
Precambrian Basement			
GAA-135	Alkali Granite	Microline	2300 ± 50
		Biotite	1900 ± 50
HN-89	Migmatite	Biotite	490 ± 12
Pre-Paleozoic Supracrustal Rocks			
BNW-44	Quartz-dolerite	Whole Rock	375 ± 10
GW-59	Phyllite	Whole Rock	410 ± 10
JH-560	Phyllite	Whole Rock	425 ± 10
Caledonian Infrascrustal Rocks (Pre Middle Devonian)			
GW-73 R[1]	Schist	Muscovite	410 ± 10
JH-146[1]	Grano-diorite	Biotite	395 ± 10
JH-105 B	Schist	Phlogopite	400 ± 10
HN-202 A	Pegmatite	Biotite	405 ± 10
Late Orogenic Intrusives			
HN-7 b	Pegmatite	Muscovite	395 ± 10
KF-111-180-182	Granite	Biotite + Muscovite	395 ± 15

[1]) Additional results which are outlined in the Postscript.

Fig. 2. Generalized tectonic map of Greenland.

As to the Paleozoic fold belts in North and East Greenland, the rock units (1) to (3) form an atectonic *stable block*: (1) Precambrian basement complexes in general, (2) Carolinidian-folded strip in Northeast Greenland and northernmost Ellesmere Island, (3) superficial cover of late Precambrian and Lower Paleozoic strata.

The ornaments (4) to (6) refer to the structural units of the *Paleozoic orogenic welts*: (4) structures of the main orogeny (of Silurian age in the East Greenland fold belt, of latest Silurian to pre-Upper Carboniferous age in North Greenland and Ellesmere Island), (5) structures caused by late orogenic spasms (Devonian), (6) post-orogenic disturbances within the Old Red basin (Upper Paleozoic).

The *younger formations* are represented by: (7) post-orogenic blanket of Carboniferous to Tertiary sediments, (8) Tertiary plateau basalts, (9) superficial tectonics of Tertiary age.

Abbreviations: North Greenland and Ellesmere Island: (G) Greely-Hazen Plateau, (H) Hall Land, (J) Judge Daly Promontory, (N) Nansen Land, (P) North Peary Land; East Greenland: (KFJ) Kejser Franz Josephs Fjord, (KO) Kong Oscars Fjord, (SC) Scoresby Sund.

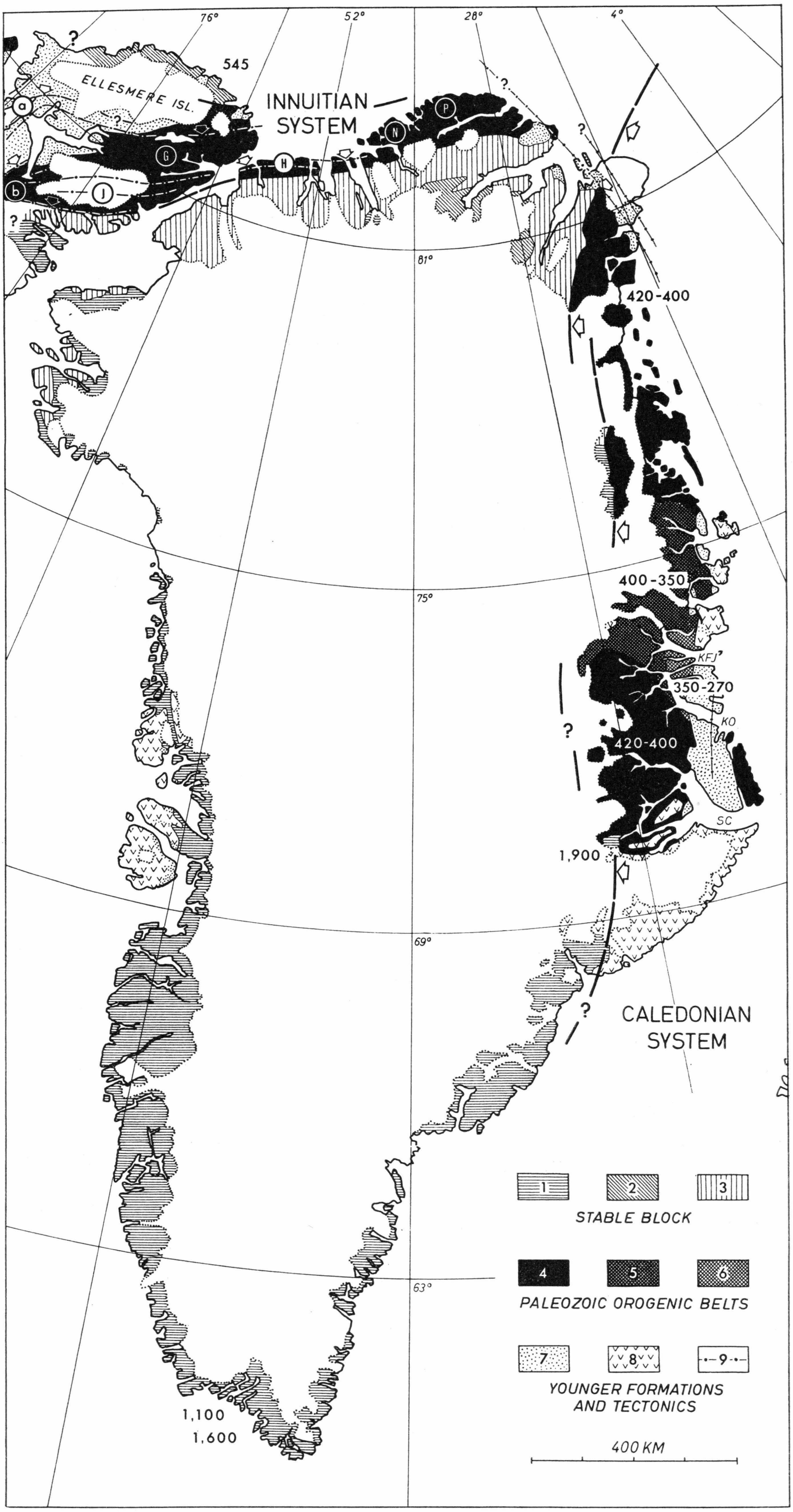

76°
52°
28°
4°
545
ELLESMERE ISL.
INNUITIAN
SYSTEM
81°
420-400
400-350
75°
KFJ
350-270
KO
420-400
SC
1,900
69°
CALEDONIAN
SYSTEM
63°
1,100
1,600
1
2
3
STABLE BLOCK
4
5
6
PALEOZOIC OROGENIC BELTS
7
8
9
YOUNGER FORMATIONS
AND TECTONICS
400 KM

Fig. 1.

1. The Precambrian Basement Complexes.

The so-called *Greenland Shield* is made up of deep-seated rock units of former mountain systems which were stabilized and worn down into low relief in still Precambrian time. Those truncated segments may have been ingredients of that hypothetical ancient continental mass *Laurentia*, which is supposed to have extended from western North America over Greenland.

In Greenland, the later border elements define those ancient rocks into a *physiographic unit*, the internal structure of which is very intricate. Most of the "shield" area is hidden under the inland ice and hence impervious to field geology. It is out of the scope of this paper to sum up the fragmentary history of the "Archean" time in Greenland.

Precambrian Basement Rocks in the Region of the East Greenland Fold Belt.

Precambrian basement rocks that have been essentially unaffected by later metamorphic events are to be found in only a few places along the western edge of the East Greenland fold belt.

Inside the Caledonian domain, rock units which were originally from the ancient basement, represent substantial ingredients of the fold belt. Owing to their *petrogenetic rejuvenation*, they have been assigned to the Caledonian crystalline (in the area south of the 76th parallel) or partly to the Carolinidian, *i.e.* late Precambrian, crystalline (in the area north of the 76th parallel). Within a sizeable portion of the East Greenland fold belt, the "Archean" basement was completely obliterated. The former metamorphic complexes underwent extensive mechanical and chemical changes. In places, as for example in the region west of Scoresby Sund (70°–72° N. Lat.) the basement exposures show less alteration and the old foliation is partly preserved.

In Figure 3 outcrops of the basement in the unaffected foreland are shown, with a tentative boundary of the areal distribution of reworked basement rocks in the fold belt.

Along the western edge of the East Greenland fold belt, two extensive **exposures of unaltered Precambrian basement rocks** are present:

(a) *Dronning Louise Land* (76°–77° N. Lat.)—PEACOCK (1956, 1958a, b) and WYLLIE (1957) ascertained that the entire western portion of Dronning Louise Land — a mountainous area with alpine peaks up to 2,200 m.— consists of intact Precambrian basement rocks, which are mainly granites, with subordinate metamorphites. The general trend of the basement structures here runs north-northeasterly.

Where the top of the basement complex is preserved, as it is the case in the western nunataks, the crystallines are sharply truncated by the major unconformity at the base of the Thule Group (Groenlandian, *i. e.* Precambrian sediments).

Towards the east this ancient pavement is bounded by a spectacular Caledonian thrust system.

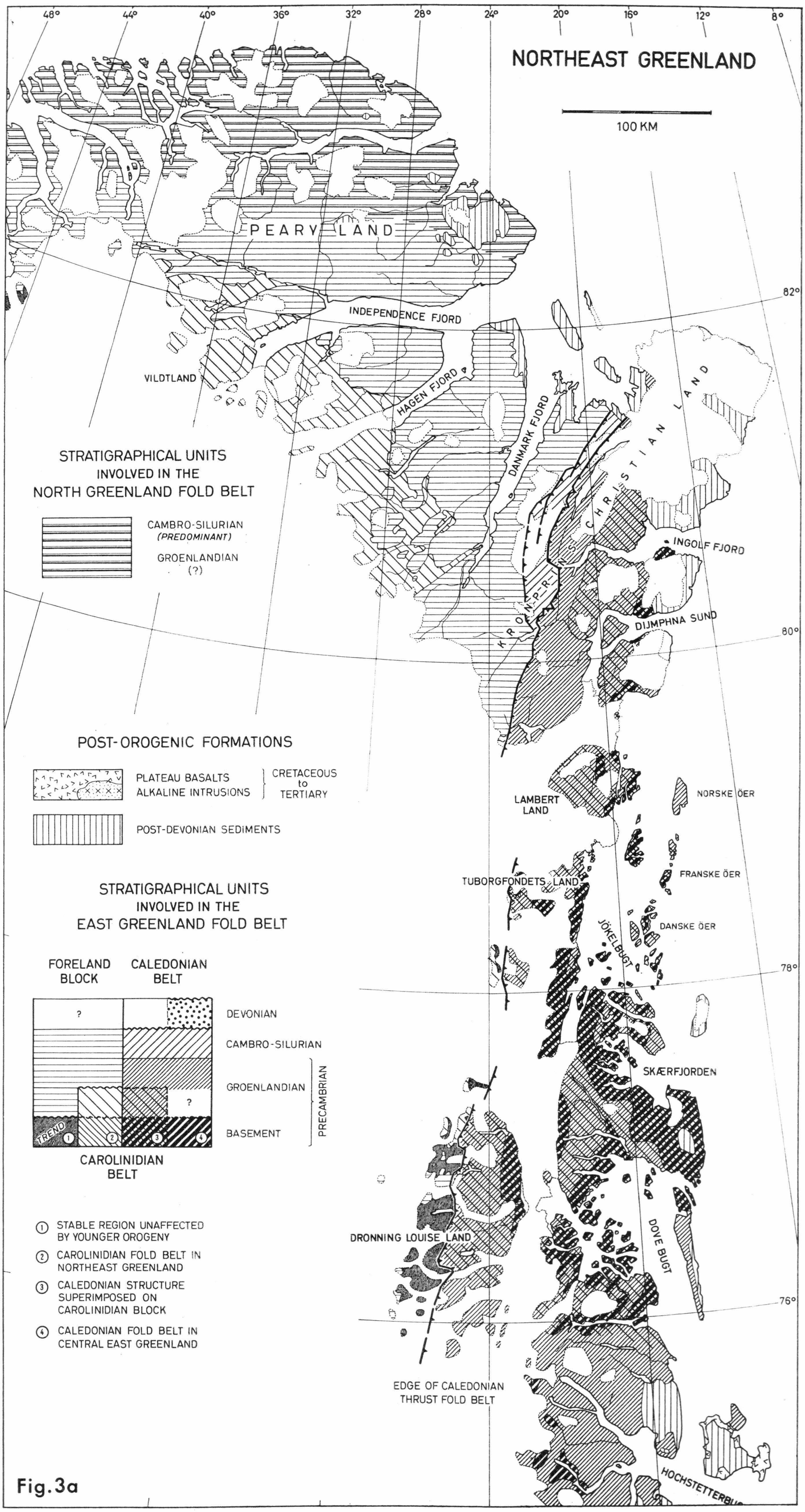
(b) *Gaaseland* (70° N. Lat.)—The southern exposure of an intact basement compartment was investigated by WENK (1961b). This outcrop bears quite a different geological setting and hence another kind of topography features.

The block in western Gaaseland is exposed in a "window", stripped by glacial erosion. Its eastern portion is an actual tectonic window in a Caledonian thrust sheet, that acted from the east. In the western portion the "window" merely represents a stratigraphic inlier. The mutual relations of the Precambrian and Caledonian rock units are easily recognizable on Figure 4, which shows a cross-section running from the foreland into the main deformed belt.

The *autochthonous crystalline basement* is made up of migmatitic-granitic rocks, generally trending west-northwest. The complex is deeply dissected by a profound sub-Groenlandian erosional interval.

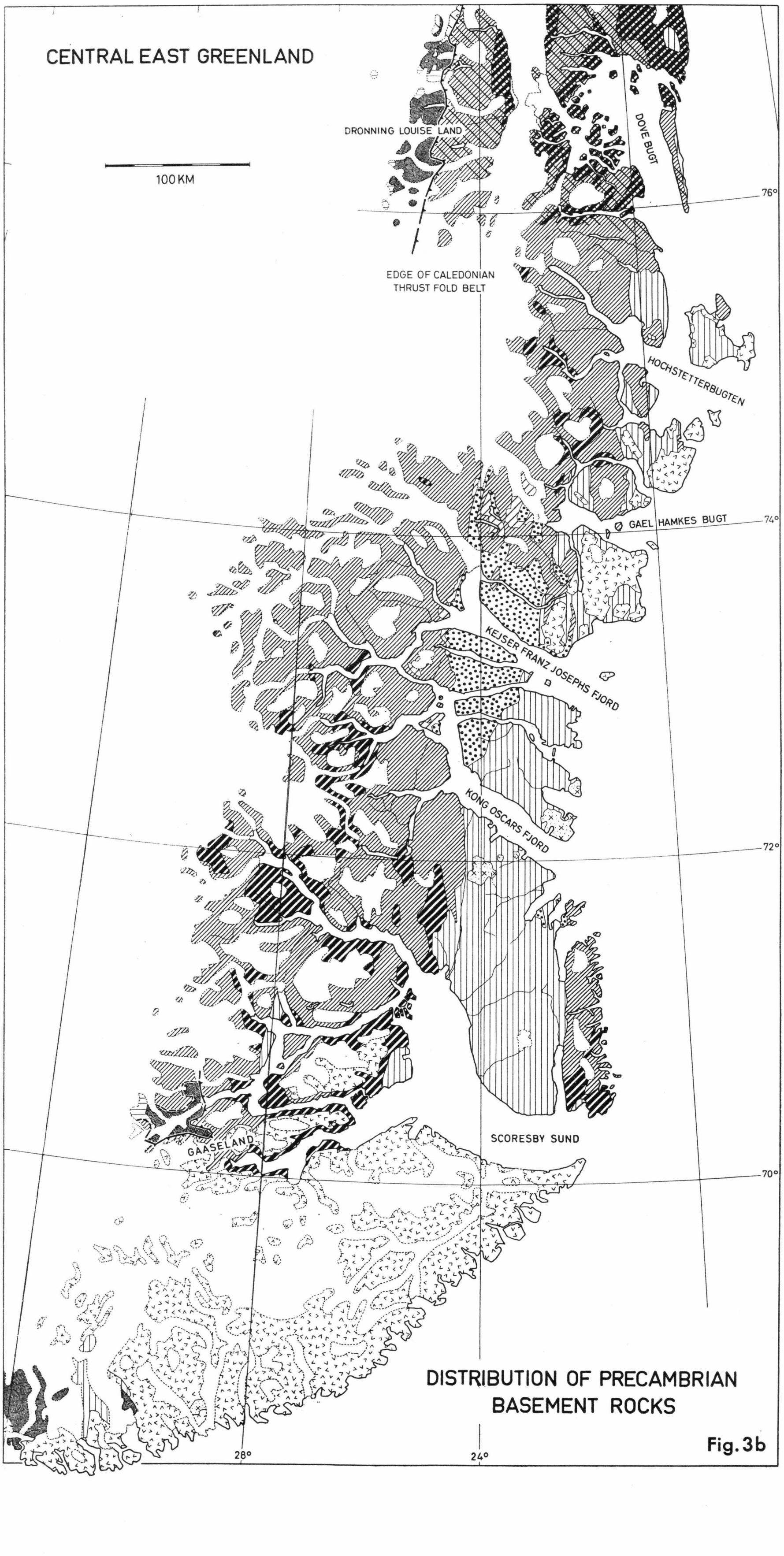
The superincumbent Precambrian strata, which represents the basal sequence of the pre-Caledonian geosynclinal column in Central East Greenland, display tillites at the base, overlain by marbles, greenschists and phyllites. Due to the overthrusting of the main Caledonian mass, an extensive sheet of reworked basement rocks, upon the foreland block, the *sedimentary cover* of the "Archean" crystallines was subjected to rolling, thrusting on a small scale, and also to low-grade metamorphism. Hence, that stratified overburden became *parautochthonous*.

WENK (op. cit., pp. 31–32) points out that in Paul Stern Land the parautochthonous Groenlandian sequence amounts to 1,800 m. in thickness and that there an *inverted succession of metamorphic zones* occurs: The flat-bedded sericite-phyllites grade upwards into staurolite and



NORTHEAST GREENLAND
100 KM
48°
44°
40°
36°
32°
28°
24°
20°
16°
12°
8°
82°
80°
78°
76°
PEARY LAND
INDEPENDENCE FJORD
VILDTLAND
HAGEN FJORD
DANMARK FJORD
KRONPRINS CHRISTIAN LAND
INGOLF FJORD
DIJMPHNA SUND
LAMBERT LAND
NORSKE ÖER
TUBORGFONDETS LAND
FRANSKE ÖER
JÖKELBUGT
DANSKE ÖER
SKÆRFJORDEN
DRONNING LOUISE LAND
DOVE BUGT
EDGE OF CALEDONIAN THRUST FOLD BELT
HOCHSTETTERBU
STRATIGRAPHICAL UNITS INVOLVED IN THE NORTH GREENLAND FOLD BELT
CAMBRO-SILURIAN
(PREDOMINANT)
GROENLANDIAN
(?)
POST-OROGENIC FORMATIONS
PLATEAU BASALTS
ALKALINE INTRUSIONS
CRETACEOUS to TERTIARY
POST-DEVONIAN SEDIMENTS
STRATIGRAPHICAL UNITS INVOLVED IN THE EAST GREENLAND FOLD BELT
FORELAND BLOCK
CALEDONIAN BELT
?
DEVONIAN
CAMBRO-SILURIAN
GROENLANDIAN
?
BASEMENT
PRECAMBRIAN
TREND
1
2
3
4
CAROLINIDIAN BELT
① STABLE REGION UNAFFECTED BY YOUNGER OROGENY
② CAROLINIDIAN FOLD BELT IN NORTHEAST GREENLAND
③ CALEDONIAN STRUCTURE SUPERIMPOSED ON CAROLINIDIAN BLOCK
④ CALEDONIAN FOLD BELT IN CENTRAL EAST GREENLAND

Fig. 3a



DISTRIBUTION OF PRECAMBRIAN BASEMENT ROCKS

Fig. 3b

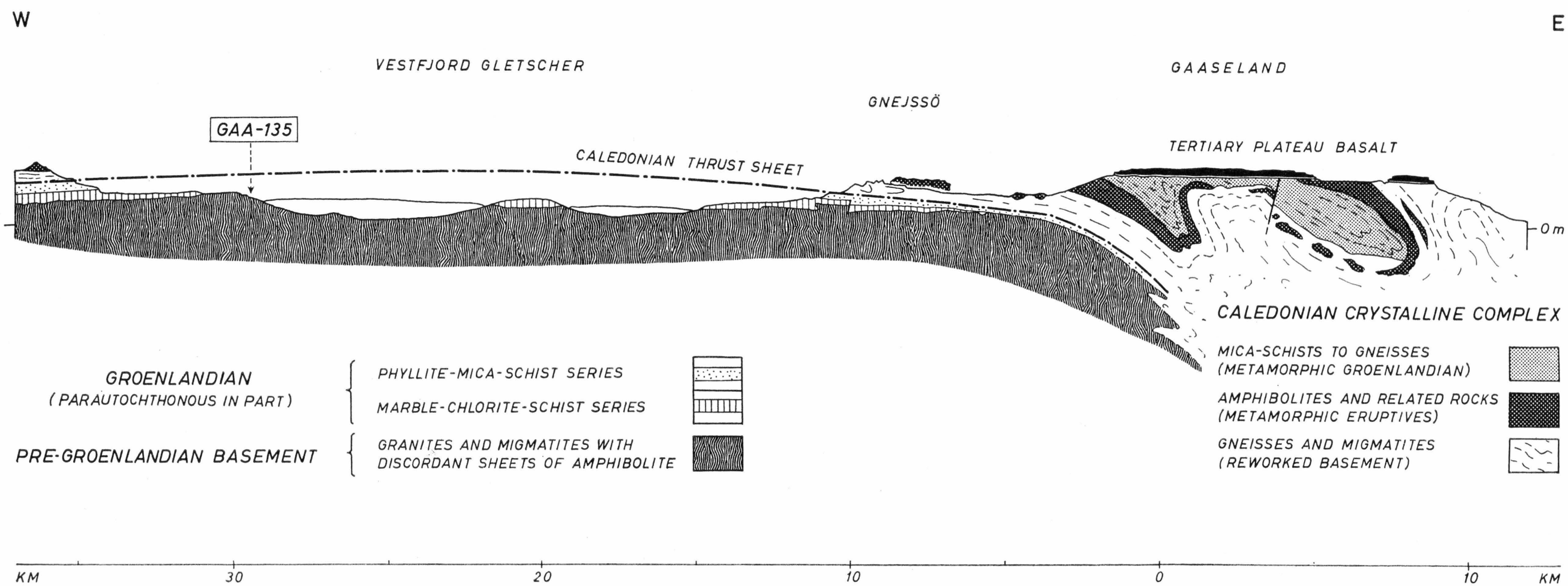


Fig. 4. Geological section across western Gaaseland and Vestfjord Gletscher showing locality GAA-135 from where a *biotite-albite-microline-alkali-granite* yielded a K-Ar age on mica of 1900 ± 50 m.y. and a Rb-Sr age on microcline of 2300 ± 50 m.y.—After E. Wenk (1961b, pl. XIII).

cyanite-bearing garnet-mica-schists (cf. Plate I). It seems most reasonable to assume that this zonal inversion is linked to introduction of heat by the Caledonian cover above.

Hence if the Caledonian metamorphic effects upon the partly overridden foreland sequence is considered, it appears that the Caledonian *orogenic heat operated laterally* according to the trace of the thrust, namely from the root zone towards the west, and that it acted *from the Caledonian overlap downward* as well. In consequence, the western portion of the "Archean" window was comparatively well sheltered from Caledonian effects by its sedimentary cover, which acted as a shield. In the eastern portion of the window, where the cover of Groenlandian sediments was pinched and rolled out to a negligible thickness under the heavy overthrust, the basement complex underwent mineral transformation and some slight mechanical breakdown. Both indicate an increasing influence of the Caledonian operations to the east.

Isotopic ages.

East Greenland—As to the age of the apparently unaltered Precambrian basement complexes exposed in East Greenland only a single date from the **Gaaseland** "window" is available. There, the K-Ar system of the biotite from a biotite-albite-microcline-granite (Sample GAA-135) yielded an apparent age of about **1900 m.y.** This is first of all a minimum date. If these rocks were deeply buried at any time in their history for a prolonged period, or if they were slightly reheated by the Caledonian event, argon would have been lost so that the true age could be much older[1]). Further measurements would be required to define the situation more closely, but this result is sufficient to demonstrate the great antiquity of the basement of Greenland.

An important observation is that this area cannot have been affected by the very extensive orogeny in Finland and northeastern Russia which produced the micas in the Svecofennian and Karelian rocks since these micas all give 1670–1800 m.y. for their K-Ar isotopic age. Prior to 2000 m.y. ago, the only large scale regional metamorphism in North America, Scandinavia or western Britain appeared to have occurred about 2600 m.y. ago, so that this Greenland basement may be that old.

Another feature is the relatively close proximity of younger rocks.

From Figure 4 it is discernible that the locality of Sample GAA-135 is only about 20 km. from the Caledonian gneiss complex, which indicates deep-seated orogenic action about 400 m.y. ago. As mentioned

[1]) See Postscript.

above, the structural trend of the basement rocks is southeast. Hence it would be possible to collect a set of similar basement samples perpendicular to the thermal gradient from this event. Approaching the Caledonian complex, the isotopic ages would decrease unless the rocks have been brought together by thrusting. In the opposite direction, still older ages may be obtained.

Another problem, which promises to offer interesting results, arises from the inversion of metamorphic zones within the sedimentary cover of the basement. Based on the geological setting ascertainable in southern Paul Stern Land, we may conclude that the present outcrop of the "Archean", of which Sample GAA-135 is representative, had been buried for some millions of years below a hot Caledonian overlap, which metamorphosed the top part of the parautochthonous sedimentary cover.

Sample HN-89 is a polygenetic migmatite from Grandjeans Fjord. The rock was originally metamorphosed as part of the Precambrian basement, yet it is in an area that has been affected by the Caledonian orogeny (cf. Figs. 3, 8, Plate IV). The isotopic age of 490 m.y. shows that the Caledonian event had caused most of the argon to have been lost. The most surprising thing about this result is that the isotopic age is not about 400 m.y. since the Caledonian effect appears to be so strong. The field relations suggest that the original ancient rock was plastically folded about a north-northeast axis which is consistent with the structural trend of the main Caledonian orogeny. Subsequent the main orogeny this gneissic area is thought to have been reheated and refolded in a transverse direction. During this event the migmatite returned to a macroplastic state which gave rise to large scale flow structures. In detail the gneissic material also remained rigid in part and then developed boudinage and shear lenticles (cf. Plate II).

If the geologic interpretation is correct, the biotite in HN-89 shows amazing retentivity. It is conceivable that it could have retained a small fraction of its argon during the last event if this was short in duration and the rocks were not hot. On the basis of all other existing data on the K-Ar biotite system, plastic deformation and recrystallization, such as occurred in the event which produced the north-northeast trend, would have caused complete loss of argon. The alternatives would appear to be (1) the north-northeast trends in this locality were actually produced in Precambrian time and the area was only lightly affected in Caledonian time or (2) the first phase of the Caledonian in this area actually occurred about 490 m.y. ago which completely restarted the K-Ar clock in these biotites and then the late Caledonian event did not significantly affect them. To settle this question more isotopic age work is required.

West Greenland.—Dates from the **Julianehaab District** in Southwest Greenland have been recently published by Moorbath *et al.* (1960). K-Ar was well as Rb-Sr determinations had been done on *micas* of mainly granitic or pegmatitic samples. As a result, in this portion of the "Greenland Shield" two mean ages were ascertained:

1,600 m.y. as to the post-Ketilidian *Julianehaab Granite*, which is unconformably overlain by the Igaliko Sandstone (Gardar Formation). The proximity of this sample to later intrusives, or the potential depth of burial is unknown so that this may only be taken as a minimum age for the basement rocks in this area.

1,100 m.y. as to *syenite massifs* of alkaline type which intruded the Gardar Formation, and hence define a minimum age for this cycle of sedimentation. These rocks have not been subsequently metamorphosed nor are they near Caledonides. Hence this date may be absolute. If the Gardar could be related to the Thule sedimentary series, a useful date for the end of Thule deposition would be available.

Mineral date provinces.—The structural outline map, Figure 2, shows the localities of these few mineral dates obtained from Precambrian basement samples. It is remarkable, by the way, that the "Archean" of Gaaseland evidently participates in one of the oldest basement complexes of Greenland. Nevertheless, to draw further conclusions about nuclear areas and continental accretion of the "Archean" pavement in Greenland would be far too speculative. Any discussion as to this intricate problem requires a vast number of additional age determinations.

2. The Carolinidian Mountain Building.

The name *Carolinidian* is derived from Prinsesse Caroline-Mathilde Alper which form the backbone of the coast mountains of Kronprins Christians Land. There, a striking stratigraphical break within the sequence of Precambrian sediments (Groenlandian) clearly shows an intra-Groenlandian diastrophism (cf. Fränkl, 1954, p. 72; 1956, p. 29; Haller, 1961 a, p. 156).

Stratigraphy.

Two stratigraphical units antedate the Carolinidian mountain building: (1) the Precambrian basement complexes and (2) a pile of

Precambrian sediments which belong to the Thule Group[1]). These cover rocks overlie the truncated Precambrian crystalline basement with profound unconformity. In North Greenland, the Thule Group represents a first cycle of late-Precambrian sedimentation.

Thulean sedimentation.—Subsequent to the planation of the basement complexes in Northeast Greenland a marginal strip of the "Shield" area became strongly negative and a geosynclinal condition was established. The general run of the basin structure was north-northwest. The strata that accumulated in the elongate basin area consisted mainly of continental detrial rocks of considerable thickness:

The *lower part* of the Thulean beds is a pelitic to semi-pelitic assemblage, up to 3,000 m thick, laterally restricted to the geosynclinal tract trending on present topography from Dove Bugt to the head of Independence Fjord.

The *upper part* of the sequence is a widespread psammitic accumulation which is up to 3,000 m thick. This sandy upper part of the Thulean beds encroached upon the cratonic area far to the west and to the south as well.

Thulean intrusives.— Everywhere in Northeast Greenland, the sediments belonging to the Thule Group are invaded by dikes and sills of Precambrian *basalts* (Thulean basalts). Subsequent to this eruption, the geosynclinal tract was thrown into folds and subjected to metamorphic action (Carolinidian orogenesis). The orogenic consolidation was followed by a second basalt invasion, together with some acid intrusions.

Tectonics.

The Carolinidian fold belt essentially occupied the geosynclinal tract where the lower Thulean strata had accumulated. Its general trend runs from Dove Bugt to South Peary Land, mainly following the cratonic border of the former geosynclinal structure (Fig. 5).

South of Dove Bugt (76° N) the Carolinidian welt strikes southeast towards the Greenland Sea. In North Greenland, in the vicinity of "Peary Channel", the fold belt disappears underneath a cover of late Precambrian and Paleozoic strata (Franklinian Geosyncline). A westerly extension of the ancient chain probably exists in the Precambrian pattern involved in the "North Ellesmere Fold Belt"[2]).

In Northeast Greenland, this late Precambrian fold belt is traceable over a distance of 800 km. In most places, however, the Carolinidian

[1]) According to KOCH's "Thule Formation" (KOCH, 1929, II, pp. 220–222).

[2]) Cf. BLACKADAR (1954), FORTIER *et al.* (1954), CHRISTIE (1957), FORTIER (1957), THORSTEINSSON and TOZER (1960).

pattern became *contorted or obliterated by the Caledonian orogenesis*, which affected the present coast area by metamorphism, thrusting, and folding. Thus, the Caledonian pattern causes quite different parts of the truncated Carolinidian chain to lie beside and over each other.

In the environs of the head of Independence Fjord, the Thulean strata are only mildly folded, nearly flat-lying in places. The axes trend easterly to east-northeasterly.

In the coastal section between 79° and 81° N. Lat., structural remnants of the deeper and shallower parts of the ancient fold belt are preserved. The dominant trend is north to northeast. To the south of the 79th parallel plastic folded systems mainly occurred; they indicate deep-seated movement about north-westerly axes.

In western Dronning Louise Land, that is, in the foreland of the Caledonian thrust-fold belt, the *original border of the Carolinidian chain* is conserved. There, strata of the second cycle of late-Precambrian sedimentation overlap with increasing angular unconformity a truncated section of Carolinidian structures, which are composed of moderately folded Thulean beds combined with the crystalline basement. The intensity of folding distinctly increases towards the northeast.

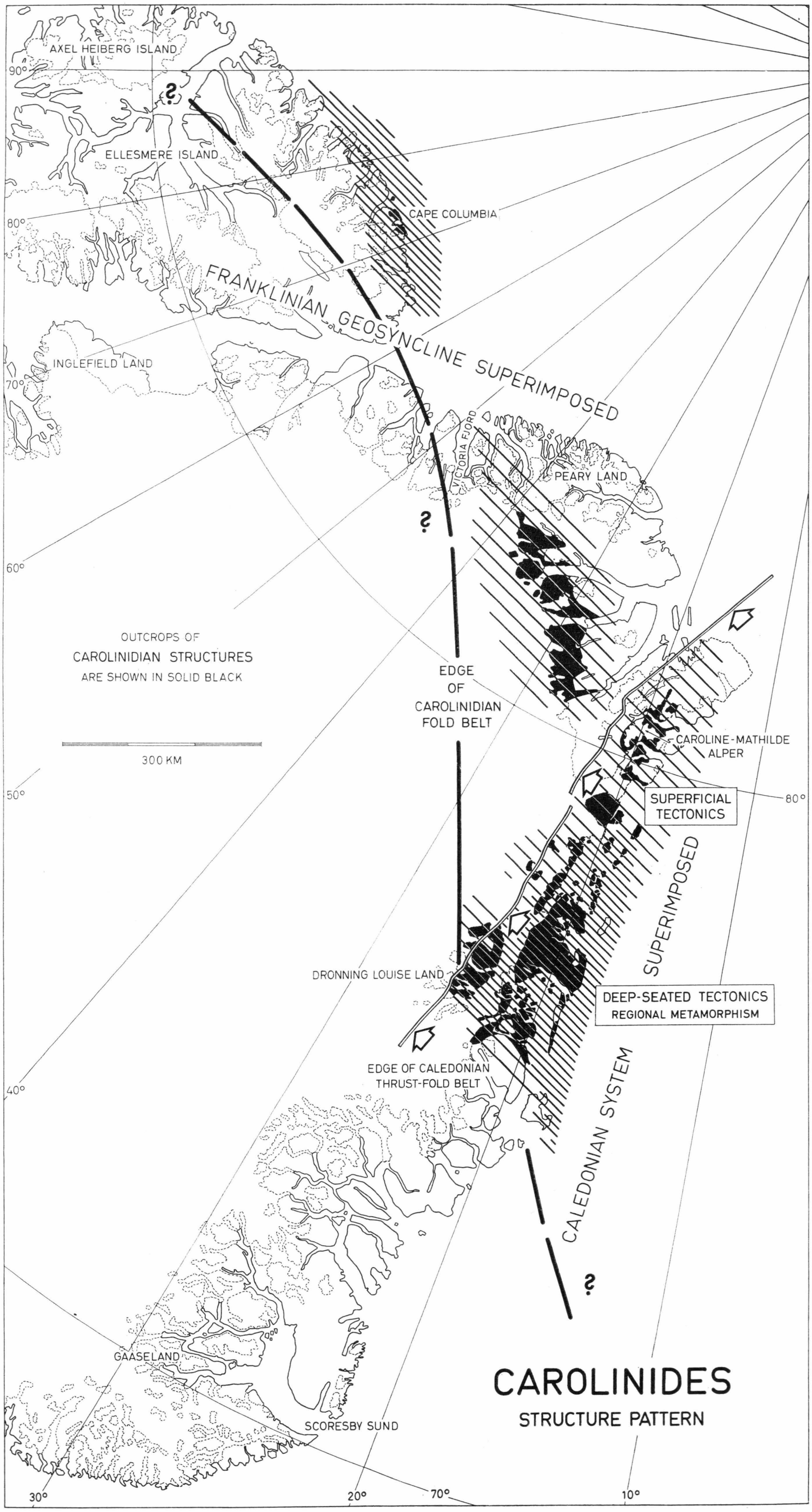
Based on the present-day arrangement of the Carolinidian exposures, it is concluded that the most intense folding and metamorphism was operative within the tract between the 76th and the 78th parallel. North of the 78th parallel the front of Carolinidian metamorphism generally decreases.

After the completion of the Carolinidian orogeny, block faulting took place and disordered that structure system. A post-orogenic generation of basalt mainly rising along fracture-planes traverse the fold belt in form of extensive dikes of considerable thickness.

Isotopic Ages.

The collection of Carolinidian rock samples did not contain samples which were surely free of effects from the Caledonian orogeny. That kind of rock would presumably be found in the coast mountains of Kronprins Christian Land where gneissified sediments of the Thule group occur in the fundamental parts of large-scale upfolds.

One sample, BNW-44, a quartz-dolerite boulder from Britannia Sö is the petrographic type of the basic *Thulean eruptives* cropping out in Dronning Louise Land. The isotopic date on a whole rock analysis gives a minimum age only of about 375 m.y. and does not tell anything about the Precambrian history. There are several possible explanations of this apparent age: (1) This particular rock type has low argon retentivity at surface temperature. Work in progress at the Lamont Laboratory



AXEL HEIBERG ISLAND
90°
ELLESMERE ISLAND
80°
CAPE COLUMBIA
FRANKLINIAN GEOSYNCLINE SUPERIMPOSED
INGLEFIELD LAND
70°
VICTORIA FJORD
PEARY LAND
60°
OUTCROPS OF
CAROLINIDIAN STRUCTURES
ARE SHOWN IN SOLID BLACK
EDGE
OF
CAROLINIDIAN
FOLD BELT
300 KM
CAROLINE-MATHILDE
ALPER
50°
SUPERFICIAL
TECTONICS
80°
SUPERIMPOSED
DRONNING LOUISE LAND
DEEP-SEATED TECTONICS
REGIONAL METAMORPHISM
EDGE OF CALEDONIAN
THRUST-FOLD BELT
CALEDONIAN SYSTEM
40°
GAASELAND
CAROLINIDES
STRUCTURE PATTERN
SCORESBY SUND
30°
20°
70°
10°

Fig. 5.

suggests that this can not exceed 40 % so that the true minimum (unheated) age might be as high as 600 m.y. (2) The sample was 100 % retentive of its argon and this rock is representative of a Devonian basalt intrusion. This alternative appears unlikely in view of the known geology, i. e., along the east coast there is no known Paleozoic volcanism north of 74° N. (3) The most likely explanation of the date is that the rock was indeed emplaced prior to the late-Precambrian Carolinidian orogeny into the Thule series but the rock was sufficiently heated by the Caledonian events to have lost its accumulated argon. The fact that the date is actually slightly younger (375 m.y.) than the final Caledonian event (see below) which appears to have occurred at 390–400 m.y. is not significant since this rock type may readily lose some argon at surface temperature.

In a previous paper (HALLER, 1961 a) it was suggested that the westerly extension of the Carolinidian belt reappears in **North Ellesmere Island.** A K-Ar determination on biotite from a *gneissic rock* from the "Cape Columbia Group" cropping out in Markham Fjord (Northeast Ellesmere Island) gave **545 m.y.** (BLACKADAR, 1960, p. 51; THORSTEINSSON and TOZER, 1960, p. 7). This is a reliable minimum age and suggests that the *folding and metamorphism* was pre-Paleozoic. The conformable sequence of Lower Cambrian, Middle Cambrian, and Ordovician strata in southern Ellesmere Island as well as in North and East Greenland also points to a pre-Paleozoic age of that orogenic action.

Two other samples from the Groenlandian series (GW-59 and JH-560) in **Central East Greenland** (see Fig. 1 for location) were also analyzed in an attempt to determine the time of the Carolinidian event. The sample JH-560 represents a shaly bed from the Quartzite Series of the *Upper Eleonore Bay Group* and sample GW-59 is derived from the uppermost bed of the *Lower Eleonore Bay Group* (cf. Fig. 6). These rocks are now both phyllites and on structural grounds it was believed that this low grade metamorphism occurred previous to the Caledonian orogeny. Earlier age work has suggested that such material, if subsequently maintained at surface temperature will retain its argon and yield reliable ages. The actual isotopic ages (**410 m.y.** and **425 m.y.**) are *Caledonian* and indicate that these areas were lightly heated during Caledonian time even though the rocks show no petrographic textures that indicate alteration or recrystallization at this time. Fig. 9 shows that both samples lie outside the aureole of regional metamorphism.

Since these ages are older than the final heating in the area (~ 390 m.y.) the apparent isotopic ages are not to be construed as the actual

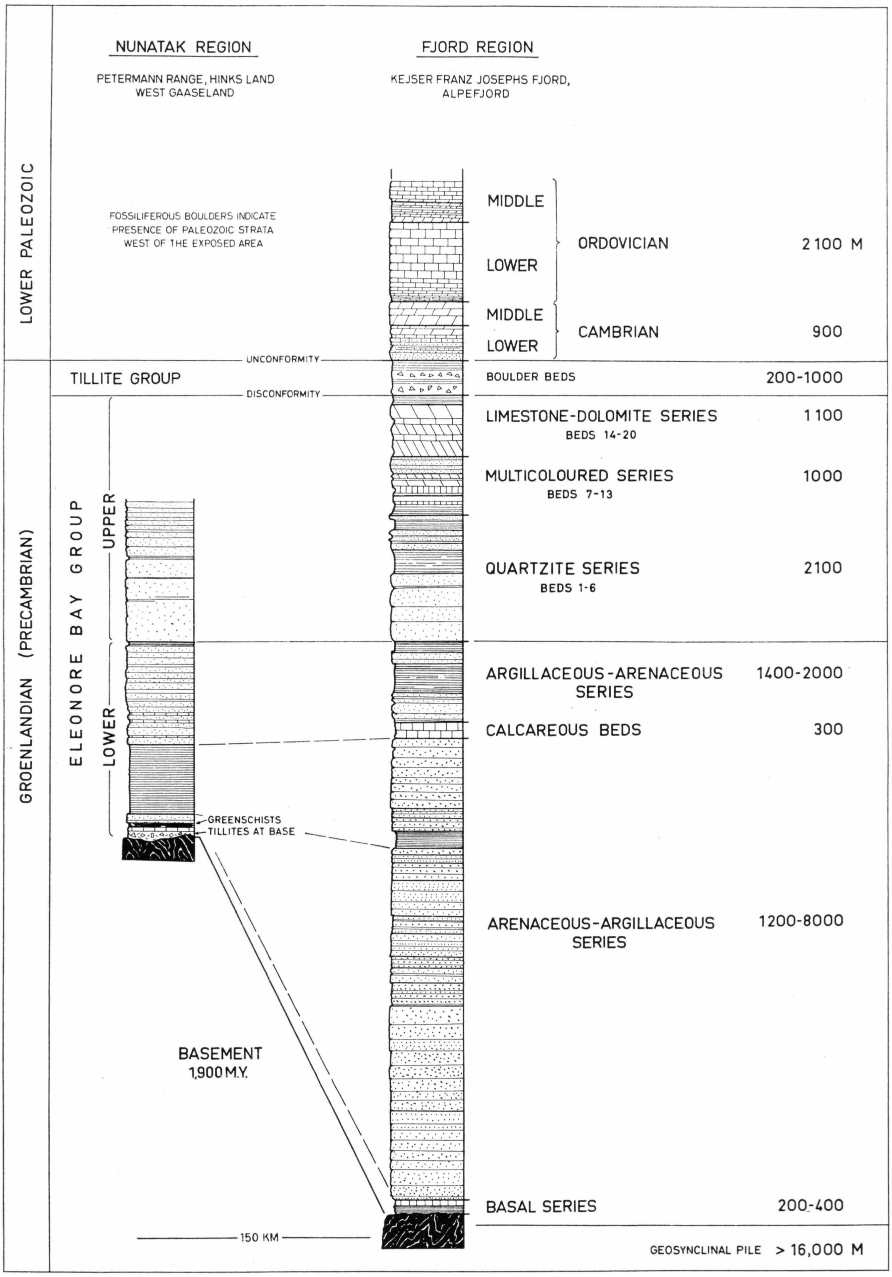


Fig. 6. Diagram showing stratigraphic sections of Precambrian and Lower Paleozoic formations in Central East Greenland. The columnar section of the fjord region is based on stratigraphical investigations carried out in Alpefjord by Dr. B. EVANS (Leicester University Expedition, summer 1961). (Private communication).

times of geologic events but rather that at some time subsequent to 425 m.y. ago these rocks were heated sufficiently to lose nearly all of their inherited argon.

3. The Paleozoic Fold Belts.

In the north and east the Precambrian basement of Greenland is welted by Paleozoic mountain belts. The orogeny which occurred along *East Greenland* developed during the Lower Paleozoic, and it is a portion of the circum-Scandic Caledonian realm. The *North Greenland Belt*, the predominant structural make-up of which is Paleozoic in age, was apparently subjected to some Cenozoic disturbance as well. This belt is a participating element of the Innuitian mountain system.

I. The North Greenland Fold Belt.

According to the stratigraphical record as well as to the tectonic pattern displayed in North Greenland and Ellesmere Island, the "Ellesmere-Greenland Fold Belt"[1]) established during two distinct periods of orogenic action: (A) Paleozoic folding and metamorphism, (B) Cenozoic folding and related movements.

Paleozoic Tectonic Pattern.

The Paleozoic diastrophism was initiated in Silurian time. Three distinct transgressions[2]) within the Silurian sequence indicate epeirogenic movements preceding the orogenic action. In North Greenland[3]) and presumably in Northeast Ellesmere Island[4]) the climax is assumed to be late Silurian or Devonian. In North Greenland no Devonian strata are ascertained. The folded and partly metamorphosed substratum of Precambrian, Cambrian, Ordovician, and Silurian sediments are overlain with distinct angular unconformity by formations which are of Upper Carboniferous age (Middle Pennsylvanian) or younger. A similar tectogenic strip[5]) with an accurate stratigraphic determination of the

[1]) A term styled by Fortier *et al.* (1954).
[2]) Cf. Koch (1920, p. 45; 1929, II, pp. 277–80).
[3]) Cf. Koch (1920, p. 72; 1929, II, pp. 280–85; 1935, pp. 131–37).
[4]) Cf. Thorsteinsson and Tozer (1960, p. 10).
[5]) "Cornwallis Fold Belt "affected at the latest Silurian time; cf. Thorsteinsson (1959), Thorsteinsson and Tozer (1960, pp. 8–9).

age of the folding occur in the central part of the Canadian Arctic Archipelago.

In Ellesmere Island and on Parry Islands[1]) clastic formations of Middle and Upper Devonian age of considerable thickness are involved in the fold-structures. This fact indicates that the western part of the Paleozoic fold belt developed in the time between the upper Devonian and the Upper Carboniferous.

In North Greenland, the Paleozoic structure pattern occupies the mountainous range north of Frederick E. Hyde Fjord (North Peary Land) and north of J. P. Koch Fjord (Nansen Land). The folds generally trend E.-W. Most of them are asymmetrical and some are overturned towards the north. In the northern half of the *North Peary Land–Nansen Land* belt long extended thrust-systems trending east-northeast prevail. The metamorphic grade of the folded and thrusted strata increases towards the north (*regional metamorphism*, cf. FRÄNKL (1955b, p. 54)).

Post-orogenic fault-systems striking east to east-southeast distort the Paleozoic pattern. Thus, North Peary Land represents a *horst block* flanked by main fractures. The age of displacement is unknown; it may be as young as Cenozoic.

Cenozoic Structures.

In North Greenland there are only few outcrops of younger strata which cover the truncated Paleozoic fold pattern. Sediments of Carboniferous, Permian, Triassic, and Cretaceous to Tertiary age were ascertained in the easternmost Peary Land. These beds had been subjected to faulting as well as local folding[2]). It seems to be most likely that this mild tectonism with a general southeast trend developed in the Tertiary. West of Peary Land no deposits subsequent to the Paleozoic folding are known.

On Ellesmere and Axel Heiberg Island strata of Carboniferous or later age are frequent. As shown by TROELSEN (1950 a, pp. 31–32; 1952, p. 209), and THORSTEINSSON and TOZER (1957, pp. 15–28; 1960, pp. 14–19) in Ellesmere Island a *pattern of Tertiary folding and thrusting is superimposed on the Paleozoic fold belt.* The younger deformation took place after the deposition of the non-marine "Eureka Sound Group" which bears fossil plants of probably early Tertiary (Paleocene or Eocene) age.

[1]) "Parry Islands Fold Belt" of Mid-Paleozoic age; cf. FORTIER and THORSTEINSSON (1953), THORSTEINSSON and TOZER (1960, pp. 9–10).

[2]) Cf. KOCH (1929, I, pp. 93–94; 1935, p. 59), TROELSEN (1950 b, pp. 6–8; 1956, pp. 82–83).

According to THORSTEINSSON and TOZER (1957, 1960) in Ellesmere Island two belts of Tertiary thrust-folding, that converge in the Eureka Sound area, are observable: (a) The northern one runs along Eureka Sound. North of Nansen Sound its fold trend swings from north to northeast, which is the general trend of the Paleozoic pattern. (b) The southern belt crosses Bay and Canyon Fjord and probably extends through Victoria and Albert Mountains and Judge Daly Promontory. Also in this area the Tertiary folding and thrusting is co-axially superimposed on the Paleozoic fold system, (cf. Figure 2).

In southern Ellesmere Island the belt of Tertiary deformation extends farther to the east (that is towards the stable area) than the Paleozoic fold belt.

In the area of the Greely-Hazen Plateau an unaffected block of the ancient Paleozoic tectogene is preserved between the two belts of Tertiary tectonic activity.

A set of vertical photographs of North Greenland which had been taken by the aerial photographic survey of the Geodætisk Institut København in summer 1960 shows a striking *thrust-fold system*, *with a distinct southward drive*, *which welts the North Greenland fold belt* between Hall Land[1]) and J. P. Koch Fjord. The structural relations indicate that the onset of this arrangement post-dates the Paleozoic tectonics of North Peary Land and Nansen Land. Thus, it seems likely that in accordance with the structural succession found in Ellesmere Island, also in North Greenland a Tertiary deformation is superimposed on preexisting fold structures, which were accentuated and thrusted by that younger orogeny (cf. Figure 2).

The initiation of the E.-W. striking thrust-faults in the area west of J. P. Koch Fjord may coincide with the formation of the normal faults, which flank the North Peary Land horst mentioned above.

Isotopic Ages.

Hitherto no rock samples from the North Greenland fold belt have been subjected to age determination. The Paleozoic metamorphics of North Peary Land should be dated to see how these events relate to the Paleozoic folding and metamorphism in East Greenland. As mentioned by KOCH (1920; see also his geological map on back cover), TROELSEN (1950 b), ELLITSGAARD-RASMUSSEN (1950, 1955), and FRÄNKL (1955b) several generations of various kinds of post-tectonic intrusives

[1]) The overthrust along the coast of Hall Land had been ascertained in terrain by W. E. DAVIES and D. B. KRINSLEY who landed in this area in spring 1960 by helicopter (private communication).

cut across the North Greenland fold belt. Age measurements obtained from such dike systems will probably make it possible to read out the post-Paleozoic evolution of the belt.

II. The East Greenland Fold Belt.

In East Greenland, from the 70th to the 82nd circle of latitude, the Paleozoic belt runs along the coastline. The observable tectogene reaches 1,400 km. in length and up to 300 km. in breadth.

The East Greenland fold belt was initiated in Silurian time. It shows a distinct westward movement towards the Precambrian platform. The belt developed during three phases of tectonic activity:

(a) *Caledonian main orogenesis* (Silurian) affected the whole east coast north of the 70th parallel,

(b) *Late Caledonian spasms* (Devonian) are restricted to the territories south of the 76th parallel,

(c) *Minor succeeding episodes* (Carboniferous to Lower Permian) caused shallow disturbances within an intramontane basin structure filled up with detritus, Old Red and partly Carboniferous in age.

The *central part* of that extensive Silurian belt indicates a deep-seated mobility and strong migmatic activity during the main orogenic epoch. From the 70th to the 76th parallel the course of the orogeny generally trends N.-S. There, a vast geosynclinal pile was subjected to folding and regional metamorphism. The intensity of deformation increases with depth. From 76° to 82° N. Lat. the orogeny created a linear thrust-fold belt directed north-northeasterly. In most places the orogenetically active tracts lie below the present exposure-level and beyond the coast in the northernmost part.

The *western border* of the belt can be seen in the westernmost *Gaaseland* (70° N. Lat.) where an inlier exposes the Precambrian basement (see above). As far as the 76th parallel, no more outcrops of the undisturbed frontland are to be seen. It is in western *Dronning Louise Land* that a N.-S. trending thrust-system outlines the edge of the orogenetically affected area. The Caledonian thrust carried blocks of ancient crystalline upon the intact foreland, that is the Precambrian basement complex partly covered by Groenlandian sediments.

In *Kronprins Christian Land*, finally, a gliding nappe of Groenlandian sediments established the western edge. It rests upon a blanket of autochthonous Lower Paleozoic strata which are displayed over a wide area of the foreland as well as in several windows in the thrust sheets.

Stratigraphy of the Caledonian Affected Rock Units.

In **Central East Greenland,** there are two principal units involved in the Caledonian main orogeny:

(C)	GEOSYNCLINAL ACCUMULATION (16,000 m)	Cambro–Ordovician	Lower Paleozoic
		——*slight unconformity*——	
		Tillite Group	Groenlandian
		—— *disconformity* ——	
		Eleonore Bay Group	

~~~~~~~~ *nonconformity* ~~~~~~~~

(A) PRECAMBRIAN BASEMENT COMPLEX

In **Northeast Greenland** we have to deal with three lithogenetic units, two of which had been subjected to orogenic action in Carolinidian time (Late-Precambrian) already:

Kronprins Christian Ld.	*East of present coast area*
(D_W) INTRACRATONIC DEPOSITS (3,300 m)	(D_E) ACCUMULATION IN MARGINAL TROUGH (5,000 m)
Hagen Fjord Group (Groenlandian) disconformably overlain by Cambro-Silurian (up to Wenlockian)	Hagen Fjord Group (restored section from Caledonian allochthone)

~~~~~~~~ *unconformity* ~~~~~~~~

(B)	GEOSYNCLINAL ACCUMULATION (6,000 m)	Thule Group (Groenlandian)	affected by **Carolinidian orogeny**
	~~ *nonconformity* ~~~~		
(A)	PRECAMBRIAN BASEMENT COMPLEX		

Figure 3 shows the areal distribution of the **Precambrian basement rocks (A)**, which are modified along the coast in most places either by the Carolinidian or the Caledonian orogenesis or both of them.

The lithology and depositional setting of the pre-Carolinidian **Thule Group (B)** had been outlined on previous pages.

The Carolinidian chain, in the progress of denudation, acted as a long-enduring positive area, which had its essential influence upon the depositional environments in Northeast and Central East Greenland.

South of the chain a **geosynclinal condition** (C) was established over a largely extended tract, which sank interruptedly in a presumably subcircular basin. Initially, the longer axis of the subsiding basin may have been directed north-easterly and on later stages directed near N.-S. The strata laid down in that geosyncline reached a thickness of about 16,000 m, the bulk of which is made of Precambrian (cf. Fig. 6).

In Northeast Greenland, to the east of Kronprins Christian Land, a smaller **geosynclinal prism** (D_E) was formed. The pile of late Precambrian sediments, now being a Caledonian allochthone in Kronprins Christian Land, approached 5,000 m in thickness. Lower Paleozoic strata are not ascertained hitherto within the allochthone.

Kronprins Christian Land itself represented a part of that positive area mentioned above during the latest Precambrian. In consequence, there the late Precambrian sediments reached only about 250 m. The bulk of the autochthonous blanket, which was laid down on a cratonic substratum, is chiefly made up of Lower Paleozoic limestone (Ordovician, Silurian). (Cf. Fig. 7).

Caledonian Main Orogeny.

(Called "old" Caledonian folding, Silurian).

In the 1,400 km long tectogene accessible today, the structural patterns of the main phase differ from south to north. The *style of deformation* was essentially controlled by the thickness of the supra-crustal pile affected by the orogeny.

In the geosynclinal tract (C) in *Central East Greenland*, where the cover was heavy and stiff, a folding developed without remarkable crustal shortening. Continuous structures with generally uniform direction prevail. A considerable part of the geosynclinal sedimentary rocks as well as the crystalline basement (A), underwent rock-transformation *in situ* by heat and granitizing agents.

Where there had been a thin stratified overburden, linear structure elements, caused by lateral thrusting, are predominant. This is a common case in *Northeast Greenland.* Intact plates of the basal pavement (A + B) were displaced by these tectonics and are now observed in thrust wedges and nappes.

Tectonic arrangements between 70° and 76° N. Lat.

The vast geosynclinal pile (C), mainly thick-bedded strata, acted stiffly against disturbing forces. The Caledonian orogeny produced a structural block with a mobile basal structure (*infrastructure*) of granitic composition overlain by a broadly folded mantle (*superstructure*) of

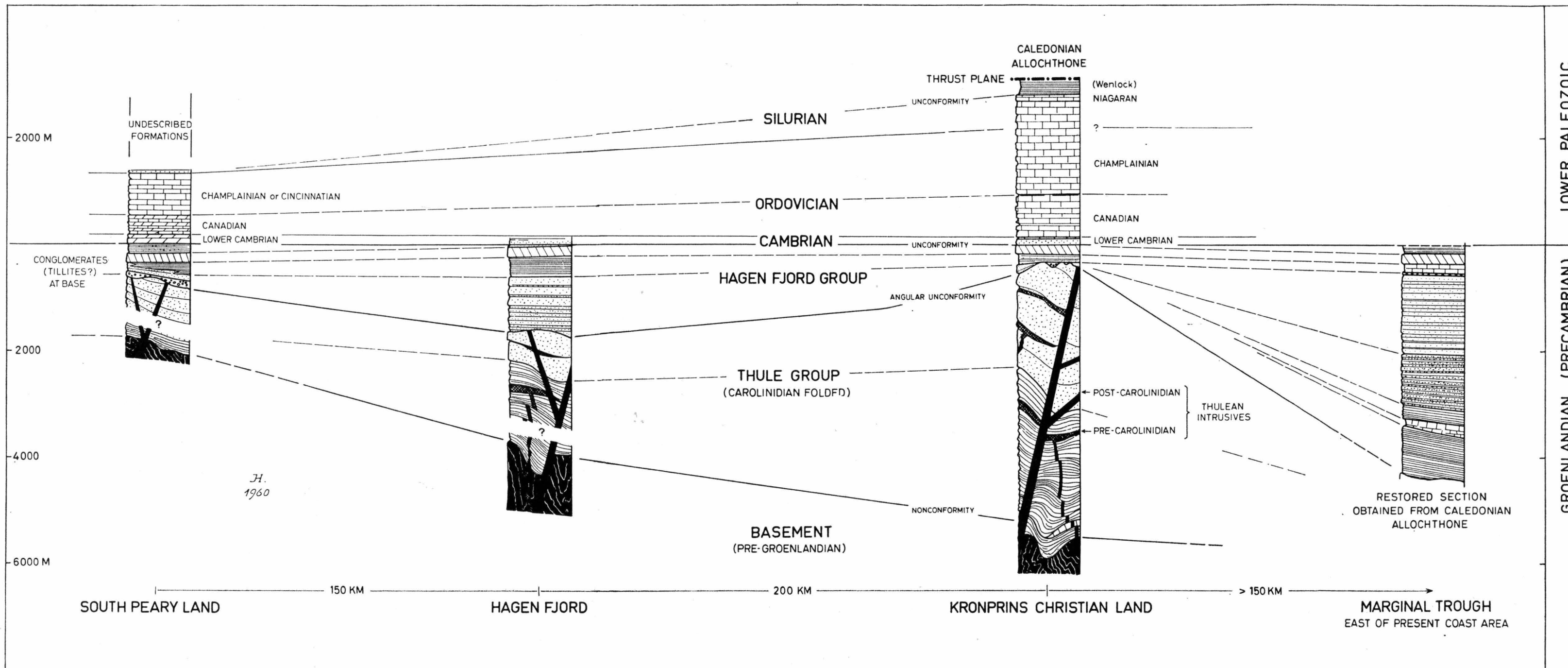


Fig. 7. Diagram showing stratigraphical sections of Precambrian and Lower Paleozoic formations in Northeast Greenland.

sedimentary rocks that underwent shallow metamorphism only. The different plastic behaviour of these two storeys gave rise to a large-scale disharmonious folding ("stockwerk"-folding[1])).

In a large area, the *front of migmatization* advanced thousands of metres into the superficial pile. Both the basement and the geosynclinal filling were involved in infrastructural conditions blurring the basal unconformity. In those places, the granitized Groenlandian sediments and their reworked basement are welded together without a seam.

In the area of the Kejser Franz Josephs Fjord, the *regional metamorphism* ascended up to the base of the Tillite Group in the columnar section.

South of the 72nd parallel, the front of Caledonian rock-transformation slightly descends. There, it is possible to distinguish between the reworked basement complex (A) and its converted cover of lower Eleonore Bay beds. (Cf. Fig. 8).

From the 74th to the 76th parallel, the tectonic and petrogenetic features attributed to the main orogeny are confused and modified by late Caledonian processes. There is some evidence that the wave of old Caledonian regional metamorphism did not reach as high a stratigraphic level as in the Kejser Franz Josephs Fjord region.

Initiated by supply of heat and influx of material, the basal part of the mobile belt was extensively modified. Vertically directed "upswellings" caused foci of granitic activity to expand into bulges and offshoots of different shape such as *domes*, *recumbent folds* (overlap up to 20 km), and even *mushroom-shaped bodies* (cf. Haller, 1955 a, pp. 80–84, 165–66).

At some places, an ill-defined portion of the granitic material is derived from the mobilized and completely obliterated ancient basement. The bulk of this highly mobile central area is composed of migmatized sedimentary rocks, as can be ascertained from the partial preservation of their original structures. From the core to the outer part of these migmatite bodies, all stages of a successive granitization occur. As the granitizing agents moved selectively into the theatre of granitization, shelled structures resulted. Thus within the migmatite bodies bands of metamorphics can still be preserved.

The deep-seated process caused the folding as well as the rock-transformation.

The *fronts of regional metamorphism* are largely conformable to the structural elements of the migmatite series. The metamorphism increases laterally and vertically. Controlled by the spatial position and shape of the migmatite bulges, the zones of equal mineral facies cut across

[1]) Cf. Wegmann (1935 a, b), Haller (1955a, 1956 a, 1957).

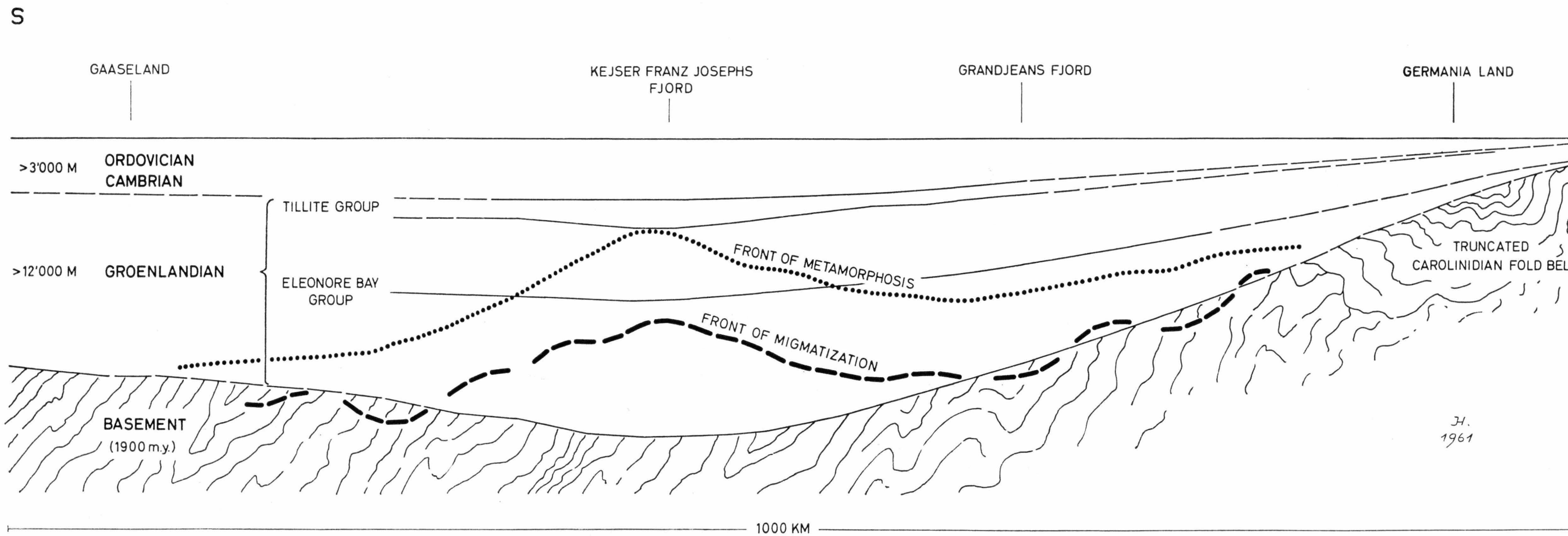


Fig. 8. Generalized representation of the ascent of the main Caledonian migmatite front and its related wave of regional metamorphism in the geosynclinal pile of Central East Greenland.

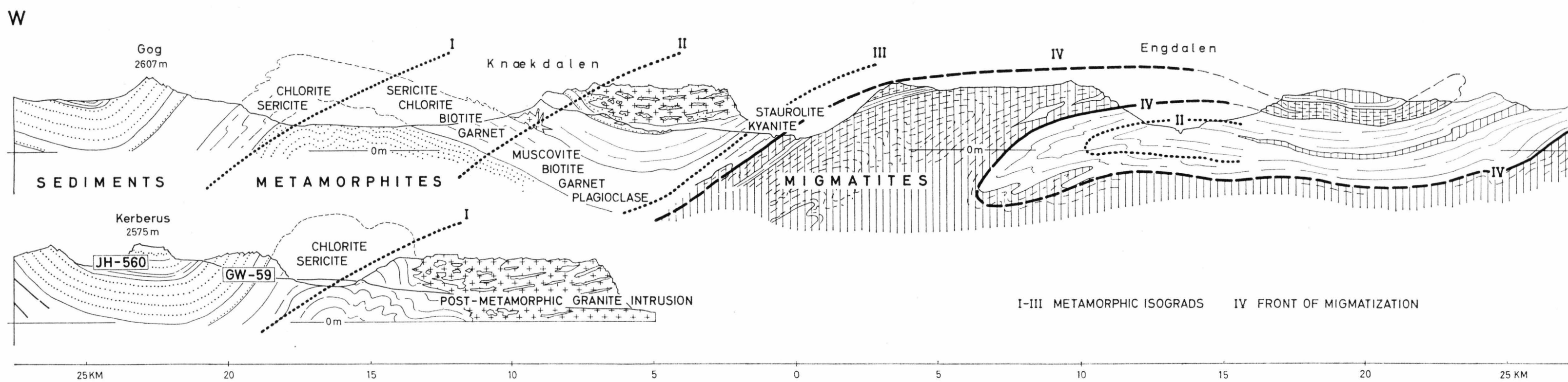


Fig. 9. Section across the main Caledonian fold pattern in Fraenkels Land showing the migmatite sheet "Hagar" and its related wave of regional metamorphism. The sheet structure as well as the enclosed recumbent fold of cover rocks are displayed by the northern wall of the innermost Kejser Franz Josephs Fjord (cf. WENK and HALLER, 1953, figs. 16, 19, pl. 2; HALLER, 1955 a, pl. 2).

the stratification and the fold-structures as shown in an example of the head of Kejser Franz Josephs Fjord on Figure 9.

In Central East Greenland, the crest-lines of migmatite bulges and the crowding B-axes of flow folds only partially follow the general N.-S. trend of the sedimentary top structure. The pattern of the deep-seated tectonics shows whorl- and bend-arrangements. (Cf. Structure Map, Plate IV).

The sedimentary cover of the initial Caledonian structure is preserved between the 72nd and the 76th parallel. Open folds of several kilometres amplitude trending N.-S. to NNE.-SSW. dominate the structural pattern. They were formed by the bulging operation of mainly vertical movement in the mobile substratum.

A zone of detachment, characterized by tectonic thickening and thinning of the incompetent strata, separates the rather stiffly folded superstructure from the mobile infrastructure.

Tectonic arrangements between 76° and 82° N. Lat.

Along the east coast between the 76th and the 82nd parallel the tectonic regimes take quite different and more various forms than south of the 76th parallel.

The difference in the tectonics can partly be explained by the pre-Caledonian evolution of this coastal section. In the area of Dove Bugt (76° to 77° N. Lat.) the orogenic belt leaves the simply built geosyncline of Central East Greenland and runs into an intricate pattern of ridges and troughs whose foundation consisted of north-northwesterly oriented segments of the truncated Carolinidian chain.

The post-Carolinidian cover (Late-Precambrian and probably Lower Paleozoic sediments) was apparently thin: Between 77° and 79° N. Lat. it may have been approximately 1,000 to 2,000 m. That area acted, at least temporarily, as a separating element between the geosynclinal depression of Central East Greenland and the marginal trough of North-east Greenland. Between 80° and 82° N. Lat. the geosynclinal filling (D_E) of at least 4,500 m Late-Precambrian strata (cf. Fränkl, 1954, 1955 a) occupied the area east of Kronprins Christian Land, which established the western edge of that marginal trough.

North of the 76th parallel, the *fronts of orogenic mobilization and metamorphism* are generally deeper than in Central East Greenland. They hardly rise over the ancient plane of post-Carolinidian denudation. To a great extent they were arrested within the Carolinidian metamorphic complexes. Vast areas were not subjected to the Caledonian metamorphism at all or merely retrogressively overprinted.

As the post-Carolinidian cover rocks varied in thickness and as the structure of its substratum differed from place to place, the Caledonian adjustments initiated a variety of local movements:

(a) The *interior of the fold belt* often shows a semi-plastic to rigid shearing of the competent complexes of the foundation with subsequent metamorphic and migmatic action, which was selectively facilitated by the pattern of the preceding mechanical breakdown.

In the region of *Dove Bugt* migmatitic upfolds trending NE.-SW. cut across the truncated Carolinidian chain striking NW.-SE. A cross-folding with zonal selection led here to an assemblage of resistant and mobile rock masses side by side. That mosaic of compartments of different ages form ingredients of that active central structure, which backs up the westward travelled Caledonian allochthone. In *Germania Land*, that is north of Dove Bugt, the pattern is entirely lost in the NW.-SE. gneiss-blocks of the Carolinidian mass. A continuous transition exists between the overprinted and the untouched ancient crystalline complex.

In the area of *Skærfjorden*, the Caledonian infrastructure comes up to the surface again. It forms here a whorl-like bulge of some 60 km diameter. The rock material consists of repeatedly reworked gneisses which originally may have been a part of the pre-Groenlandian basement, but then were modified by the Carolinidian and again by the Caledonian orogeny. At the western margin of the Skærfjorden Complex, north-northeasterly trending bunches of Carolinidian gneiss-folds were co-axially overprinted.

In the southern part of *Jøkelbugten*, ancient rock complexes have been refolded plastically and also been rejuvenated in part. Along the *coast of Tuborgfondets Land*, the Caledonian metamorphism was equally operative. There, the southern sections were overfolded plastically and the northern ones semi-plastically. The north-northeasterly gneiss-folds originated in a co-axial refolding of the Carolinidian structure by the Caledonian pattern. On the northern islands of *Jøkelbugten*, the Caledonian movements merely produced shearing of rigid rocks. Between the pre-existing complexes that were left intact and the Caledonian flow-fold structures there are broad transitional zones. North of the 79th parallel outcrops of the Caledonian gneiss-folds are rare. Some north-northeasterly trending upfolds appear in the coast area of *Lambert Land*. There, as well as in the northern sections of the coast-mountains of Tuborgfondets Land, late-tectonic pegmatites settled along a pattern of shear-planes, which were directly controlled by the adjustments of upfolds mentioned above.

Along the east flank of the *coast-mountains of Kronprins Christian Land*, it is possible that further Caledonian gneiss complexes occur. North of Jøkelbugten though, the actual fundamental structure of the Caledonian belt runs to the Greenland Sea.

(b) The *outer portions of the orogenic belt* bear all features of a marked tectonic drive towards the west. Upthrusts, overthrusts, and nappe-arrangements build the western edge of the belt throughout.

In *Dronning Louise Land*, low-angle thrust planes striking NNE.-SSW. carried slabs and blocks of ancient crystalline complexes as solid masses over the intact pre-Groenlandian basement. Whilst the frontal parts of the Caledonian allochthone and their immediate foreland —except for weak stress-metamorphic effects—show no traces of Caledonian metamorphism, the thermal action increases towards the east, that is, towards the interior of the belt. In Central Dronning Louise Land, the influx of heat and material is to a great extent restricted to the zones of thrusting between the resistant blocks. The ancient gneisses and schists in eastern Dronning Louise Land underwent a thoroughgoing reheating and in consequence they were plastically overfolded. In Dronning Louise Land, the amount of thrusting is not known. The active backbone of that forethrust is exposed in Dove Bugt mentioned above.

In the westernmost *nunataks of Tuborgfondets Land*, Caledonian thrusts acting from the east created a parautochthonous imbricate arrangement. Similar structures are to be found in *Lambert Land*, where westward travelled plates and blocks grade into the plastically overfolded gneisses of the coast area.

The striking assemblage of nappe and peel thrust structures within the coast range of Kronprins Christian Land bears all the features of superficial tectonics. The orogenically active elements are deeply buried here. The focus of Caledonian heat must have been very deep in this part of the belt, since the entire mass of the filling of the marginal trough, at least 4,500 m thick, pushed over from the east, is practically unmetamorphosed. In Central Kronprins Christian Land far-travelled thrust-masses are probably due to gravitational gliding tectonics (cf. Fränkl, 1954, 1955 a). The frontal nose of the 40 km wide nappe trends north-northeasterly. In its foreland, the autochthonous plate of Precambrian and Cambro-Silurian strata was subjected to shallow folding. Frontland-folding and nappe structures show co-axial trend. The root zone of the nappe structures lies in the east of the Caroline-Mathilde Alper. This mountainous backbone is made up of fractions of the Carolinidian trunk split up into thrust wedges by Caledonian underpinching.

The autochthonous to parautochthonous basement wedge uplifts in the coast range between 80° and 82° N. Lat. as well as the similar structural units between Lambert Land and Dronning Louise Land, are thrust bodies pushed westward by active foci. Between 76° and 80° N. Lat. those orogenetically active centres of movements come up to surface only in strips.

To sum up: The northern portion of the East Greenland fold belt was under the influence of remarkable tangential crustal movements, which left a strong linear structure behind. The north-northeast trend of this Caledonian structure shows an astounding constancy over a distance of more than 600 km, that is from southern Dronning Louise Land the northern Kronprins Christian Land.

Isotopic Ages.

In Central East Greenland, the pre-Caledonian sequence ends with Middle Ordovician beds, above which is a stratigraphical gap up to the lower Middle Devonian. In former times there was a tendency to bring that gap in connection with Taconic, *i. e.*, Ordovician movements (cf. WEGMANN, 1935 a, p. 49). It has been shown (KULP, 1961) that the absolute time for the Trenton deposition in North America (start of Upper Ordovician) or the base of the Carodocian in Sweden is 440 ± 10 m.y. Thus the movements which initiated the Caledonian orogeny began at or subsequent to this date. Any older age in this area represents the actual time of a Pre-Cambrian event or an intermediate apparent age developed by partial loss of argon by the Caledonian orogeny rock or sample HN-89 discussed above.

After the world war II additional results from Kronprins Christian Land became available. FRÄNKL (1955 a, p. 24) showed Caledonian nappe structures superimposed on Silurian beds, as young as Wenlockian. Based on structural studies carried out in the years 1955–58 over the whole East Greenland fold belt (cf. HALLER, 1961 b), it became evident that the main orogeny in Central East Greenland coincides with the initiation of the post-Wenlockian nappe structures in Northeast Greenland.

The isotopic ages, related to rocks formed during the Caledonian main orogenesis, support that conclusion. Thus it seems satisfactorily shown that in East Greenland the *principal mountain-building* took place in *Silurian* time, probably in the upper part of this epoch, that is 420 to 400 m.y. ago. According to the latest definition of the geological time scale (KULP, 1961) the end of the Silurian is placed at 405 m.y.

The *onset of the Caledonian* metamorphosis in *Central East Greenland* can not be determined from any of the existing samples, indeed it may be impossible to make such a determination unless a locality could be found which was affected only by the initial metamorphism and then was rapidly cooled and remained near surface temperature for the duration of the Caledonian period.

The **end of the main orogeny** is best defined by sample HN-202A from Lambert Land (79°30′ N. Lat.). This sample gave an age of **405 ± 10 m.y.** which lies at the Silurian-Devonian boundary.

HN-202A represents a *late-tectonic pegmatite*, which intruded the latest shearing pattern in the coast area of Lambert Land. The emplacement of that pegmatite dates the relaxation of Caledonian activity in Northeast Greenland. There was no further metamorphic activity in this area so that this may be an absolute age.

Sample JH-105 B is geologically from an early stage of the main orogeny. This *phlogopite-diopside-schist* is derived from one of the earliest upwarpings of the infrastructure in Central East Greenland, that is "Migmatite Dome Nigglis Spids" (cf. HALLER, 1955a, pp. 84–95, 166–167). The locality of Sample JH-105 B is to be seen on Plate III. The age of **400 ± 10 m.y.** means either (1) the time between the early upwarping and final pegmatite intrusion was short, or, (2) the area was hot enough at the end of the major Caledonian orogeny to have caused loss of all radiogenic argon formed during the period between initial schist formation and the final pegmatite formation (see Fig. 10). The maximum time interval involved can not exceed 30 m.y. (or all of the Silurian) since sedimentation occurred through middle Ordovician time as noted above.

Late Caledonian Spasms.

(Called "young" Caledonian folding, Devonian).

Late Caledonian spasms are restricted to the territories south of the 76th parallel. In the latest stage of the main orogeny, that portion of the Caledonian chain was subjected to extensive *tension*. Traces of that widening are discernible through the whole structural edifice: In the deeper storeys of the fold belt traces of that crustal widening are seen in paracrystalline monoclinal folding. The shallower parts were rigid enough to be fractured along slightly inclined slip faults, the total displacement of which approach a considerable amount[1]) in places.

The *late-orogenic tension structures* preferably occur along north-

[1]) FRÄNKL (1953, p. 50) examined a 42 km long cross-section in North Scoresby Land, where tension fracturing was extremely operative. He obtained a widening of 135 per cent.

Fig. 10. Around Renbugten, that is the locality of Sample JH-105 B, the migmatite dome is crossed by many post-tectonic pegmatites (see Plate III), which apparently had their influence upon the radiometric systems within the country rocks. The photograph from Renbugten portrays the relationship between one of these alkali-feldspar pegmatites (to the left) and the gneissose country rocks, which are related to the Sample JH-105 B. The emplacement of the pegmatite caused a remarkable heat acting upon the gneisses, which are softened up within a contact zone of about 0.5 m.

northwesterly trending lineaments. Between the 72nd and the 76th parallel the ancient fold belt was divided by alignments of compound slip-fault systems into *three structural provinces*: (1) a northern high ground, (2) a down-flexed graben-like tract, and (3) a southern high ground (cf. Fig. 11).

Northerly to north-northeasterly striking step-faults led to further differences of level in the truncated old Caledonian belt. A fundamental NNE.-SSW. fracture runs from Skærfjorden (77°30′ N. Lat.) through Dove Bugt, Kong Wilhelms Land to the terminus of Waltershausen Gletscher (74° N. Lat.). That disruption apparently preceded the pattern of north-northwest alignments but was repeatedly renewed during the Devonian.

The large-scale mosaic of fault-blocks was differentially affected by the young Caledonian spasms. The nature and style of the overfolding are completely different within the provinces (1) to (3). There is also a succession in age that is fairly well proven by the record of Devonian strata. The overfolding of the northern high ground (1) antedates the fold-systems within the Old Red basin (2).

Isotopic ages.—Sample HN-7 b represents coarse pegmatitic muscovite from a post-tectonic granite intrusive which probably occurred just subsequent to the termination of the Caledonian metamorphism within Province (1). The age of 395 ± 10 is probably an absolute one. It is considered highly significant that the *early post-tectonic Caledonian granites* of Britain fall precisely in this age range. (Kulp, *et. al.*, 1960). Thus on both sides of the North Atlantic the Caledonian must have begun after 440 m.y. ago and had been completed by 390 m.y. The most probable time for the maximum is latest Silurian with tectonic activity being completed by the end of the Lower Devonian.

(1) The Lower to Middle Devonian overfolding of the northern high ground.

The first late Caledonian spasm affected the area between Clavering Ø (74° N. Lat.) and Bessels Fjord (76° N. Lat.) by a folding of NW. trend. This is transverse to the main Caledonian structures. The active centre of tectonism lies in Grandjeans Fjord (75° N. Lat.) where infrastructural conditions revived.

In the *northeast* an echelon thrust-system outlines the boundary of the young Caledonian regime, which caused a lateral push acting from the Grandjeans Fjord focus. The *western edge* of the refolded segment is the fundamental fracture mentioned above. Only in few places the traces of refolding go to the west beyond that line.

The *southern boundary* of the refolded tract was disguised by the imposition of Province (2), which apparently acted as a back-trough of the new orogenic belt. In Payers Land and on Clavering Ø, folds plunging gently on southeast axes as well as related shear planes interfinger with the pre-existing northeast framework.

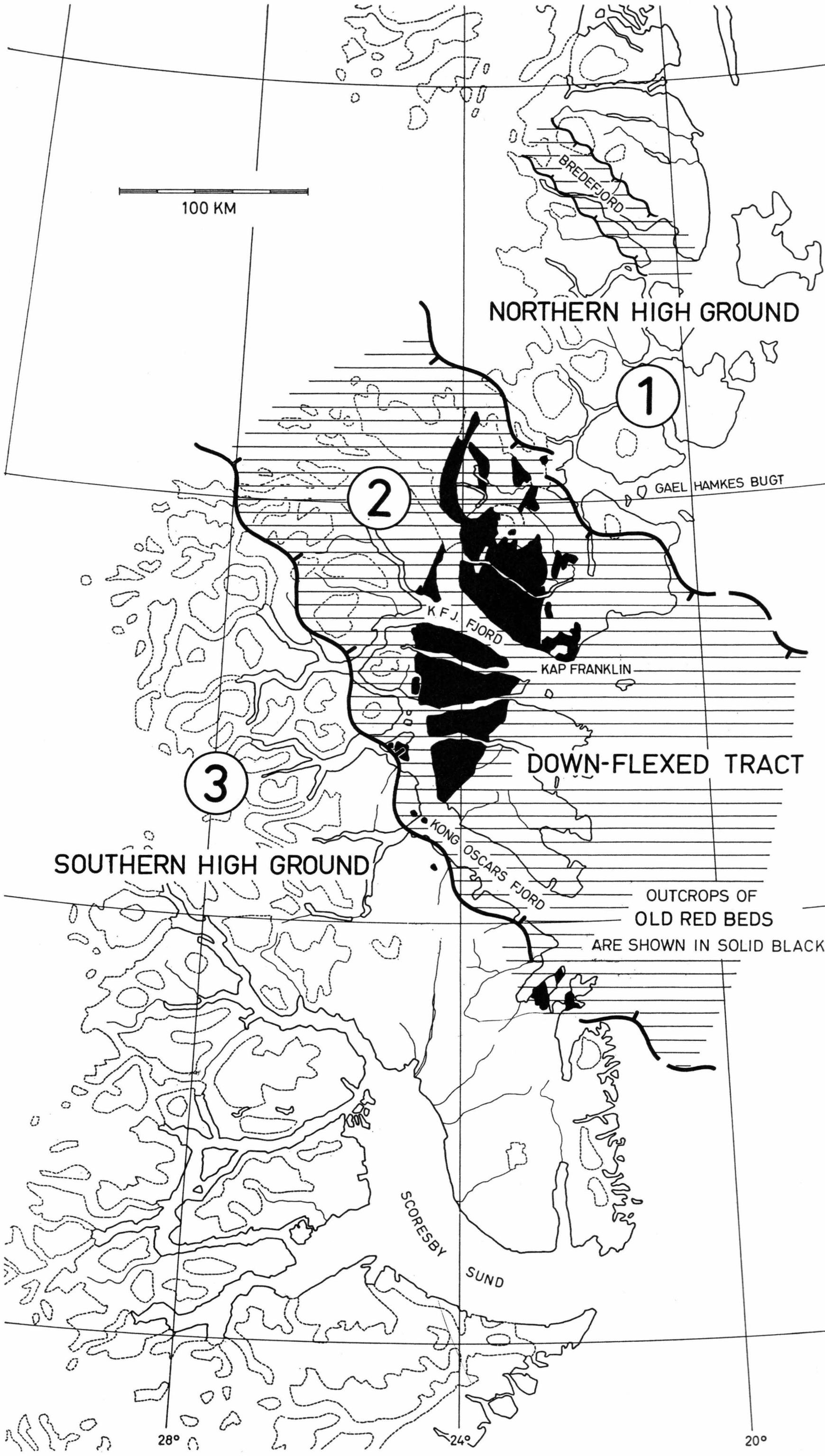


Fig. 11. Late Caledonian structural provinces.

In Province (1) no Devonian deposits had been found *in situ.* All the rock units affected by the revived orogenic action hitherto were ingredients of the old Caledonian structure: (a) the *pre-Groenlandian basement* reworked and obliterated by the Caledonian is exposed in the area between Grandjeans Fjord (cf. Sample HN-89, p. 24) and Clavering Ø, (b) *metamorphic* strata of the *Lower Eleonore Bay Group*, and (c) *non-metamorphic* sediments of the Lower and Upper *Eleonore Bay Group* which were parts of the former superstructure. These beds prevail in the environs of Bredefjord and Ardencaple Fjord where a northwesterly trending sag was formed before the refolding took place.

The rocks distorted by the young Caledonian spasm are transgressively overlain by Jurassic detrital sediments. Hence there is a considerable gap in the stratigraphical record.

The young Caledonian movement pattern.—The structural elements of the old Caledonian belt generally trend northeasterly. The tight gneiss-folds of its infrastructure and the open arches of its non-metamorphic superstructure run co-axially in the whole area. The superimposed pattern everywhere trends northwesterly demonstrating a *cross-folding* on a large scale. (Cf. HALLER, 1957).

The area around Grandjeans Fjord displays the *infrastructural centre* of the young Caledonian belt. The gneiss-complex produced during the main orogeny was remobilized and rejuvenated by chemical and thermal action. The reactivated migmatites show a strikingly fresh habit, although the mechanical breakdown of earlier foliation is conspicuous (cf. Plate II). The young and old fold-axes cross at right angles, but the superimposed northwest pattern dominates the structural make-up. The cross-folding took place in a plastic condition, which is presumably connected with an inherited orogenic heat of the early Caledonian. Of the former architecture merely fragments of steep axial plunge folds are left. The young flow-structures expand towards the north-northeast. Their axes are horizontal or plunging gently, mainly to the southeast.

In the *anteroom* northeast of the Grandjeans Fjord focus lie parts of the ancient block which were refolded about corresponding axes and thrust north-northeasterly. The displaced masses mainly consist of the material of the former superstructure.

The earlier fault-pattern related to the fundamental north-northeast line was subjected to strike-slip displacement of all dimensions. A grand-style flaw occurs along the northwestern edge of the refolded area, namely in Kong Wilhelms Land.

A *thrust mass* of unmetamorphosed sediments lies on parts of the old Caledonian infrastructure. Its frontal nose runs from the head of

Bessels Fjord to the northern edge of Shannon Ø. South of Bessels Fjord the horizontal displacement amounts to 5–10 km.

The crystalline area in front of the nappe-structure is traversed by several shear planes running parallel to the dominant thrust. In several places, a granitic melt synkinematically rose into these low-angle faults.

After the folding and thrusting had ceased, other *intrusive granites* forcibly intruded into the fold belt. Two of these intrusives of batholithic dimensions cut across the displaced sedimentary mass. A third batholith lies in the transitional zone between the sedimentary rocks which were pushed northeasterly and the active infrastructure (cf. Fig. 12).

Isotopic Ages.—Due to the lack of Devonian strata within the refolded tract, it was not possible on stratigraphic grounds to give an accurate determination of the age of the initial young Caledonian push. It was assumed to be Upper Devonian (Haller, 1956 a, p. 21) but later on investigation of the structural trends in the area south of Grandjeans Fjord and its relation to the stratigraphically dated Middle and Upper Devonian tectonics in Hudson Land (cf. Bütler, 1940, 1959), it became apparent that the Grandjeans Fjord push preceded the Hudson Land pattern (cf. Haller, 1961 b). The isotopic age measurements are in agreement with that finding, *i. e.*, that the younger Caledonian folding within Province (1) occurred in *Lower to early Middle Devonian* time.

Two rather accurate dates concerning the upper age limit of this younger Caledonian spasm are available:

At the head of Bredefjord, a stock of *intrusive granite* cuts across the young Caledonian thrust mass (cf. Fig. 13). The batholithic invasion took place after the refolding and thrusting caused by the Grandjeans Fjord focus. Sample HN-7 B represents a pegmatitic variety of this **post-tectonic granite,** the muscovite of which yielded an age of **395 ± 10 m.y.**

At Kap Franklin, that is inside the basin tract (2), an analogous **granite** batholith, well proven by the stratigraphical record as **Middle Devonian,** showed a similar mica age (**395 ± 15 m.y.**). Also the Kap Franklin Granite (Samples KF-111, 180, 182) is a *post-tectonic intrusive.* It broke through a vast accumulation of Middle Devonian clastics ("Vilddal Series"), which underwent folding about westerly to northwesterly trending axes before the granite invaded. The basal part of that coarse detrital series, which bears fossil fishes, as well as its basal contact are nowhere exposed. Thus no criteria will satisfactorily answer the question about the relationship between the formation of the Vilddal beds, their subsequent distortion, and the occurrence of the young Caledonian belt in the northern high ground. These clastics must surely be waste products accumulated at the foot of the young Caledonian chain

The striking agreement as to the age of the two batholithic markers lead to the conclusion that the post-tectonic intrusives widely distributed in the refolded northern positive tract (cf. Fig. 12) correspond to the Kap Franklin Granite, which invaded the lowermost beds accumulated in the back-trough of the Grandjeans Fjord mountain belt.

As shown on Figure 14, adapted from Bütler's paper concerning the Kap Franklin area (Bütler, 1954), the Kap Franklin batholith, stuck fast in its northwesterly folded Middle Devonian country-rocks, was truncated and unconformably overlain by another Middle Devonian sequence ("Kap Franklin Series") indicating volcanic activity in the northern portion of the basin structure (2).

These data suggest that the young Caledonian folding and thrusting which affected the structural province (1) acted during the Lower or the early Middle Devonian, actually prior to the emplacement of the batholiths with mica ages of about 395 m.y. On the other hand the errors are sufficiently large that HN-7b intrusive could be considerably younger than KF-111, 180, 182. It appears unlikely, however, that the latter could have been emplaced later than 380 m.y. ago which would still be in the Middle Devonian.

(2) Middle and Upper Devonian fold-systems in the downthrown basin tract.

A flexure line, which coincides with the course of Wordies Gletscher, established the northeastern edge of the subsided tract. The southwest edge runs from West Andrées Land to EastL yells Land and from there along Kong Oscars Fjord to Canning Land (cf. Fig. 11).

The basin is open towards the east. Towards the west the keel of that intermontane basin tract is lifted step-like by northerly running faults as mentioned above. The entire depression comprising the systems of Kejser Franz Josephs Fjord and Kong Oscars Fjord was named "Royal Bay" by Koch (1935, p. 78).

The stratigraphical units involved in the Middle and Upper Devonian structural pattern are as follows: (a) The *basement of the basin* consists of the truncated old Caledonian superstructure, *i. e.*, Groenlandian and Lower Paleozoic beds. (b) The *sedimentary filling* represents a post-orogenic accumulation of Middle and Upper Devonian detritus, partly interbedded with products of a repeated volcanic activity. The total thickness of the Old Red, the depositional setting of which is most intricate in detail, reaches more than 7,000 m. The basal beds overlap nearly 8,000 m strata involved in old Caledonian folding (cf. Bütler, 1957, pp. 19, 74; 1959, p. 168).

In the basin province (2) manyfold tectonic events may be traced. Yet only in the area of Hudson Land (74° N. Lat.) it is possible to restore

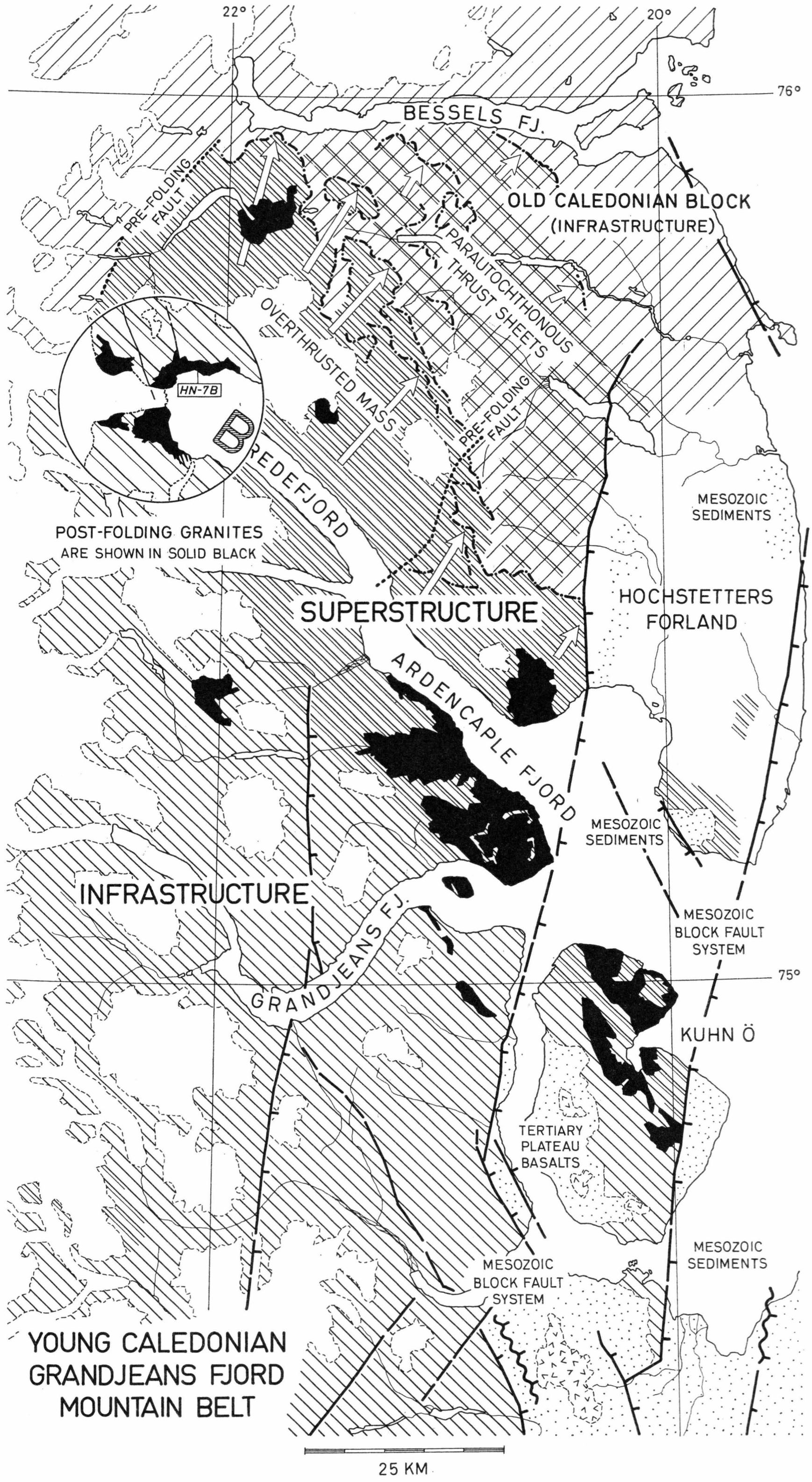


Fig. 12. Tectonic map showing the Lower to early Middle Devonian pattern in the area of Grandjeans Fjord.

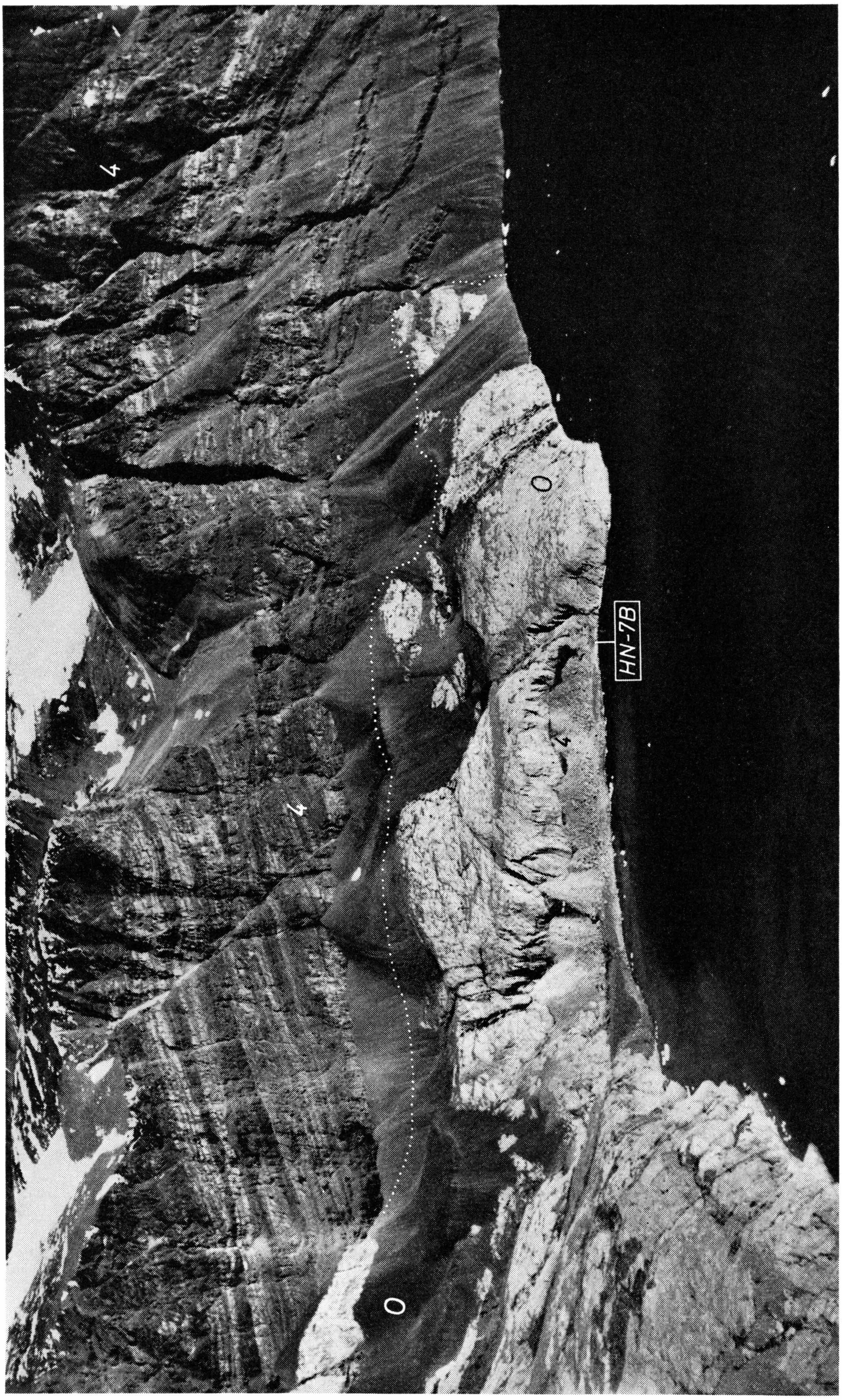


Fig. 13. Granite batholith at the head of Bredefjord (cf. Figure 12). The aerial photograph shows locality HN-7 B on the northern fjord wall, the whole of which is 1400 m in height. This post-tectonic granite (0) cuts across low-grade metamorphic quartzites (4) of the Lower Eleonore Bay Group which are involved in the thrust-fold belt caused by the Grandjeans Fjord spasm.

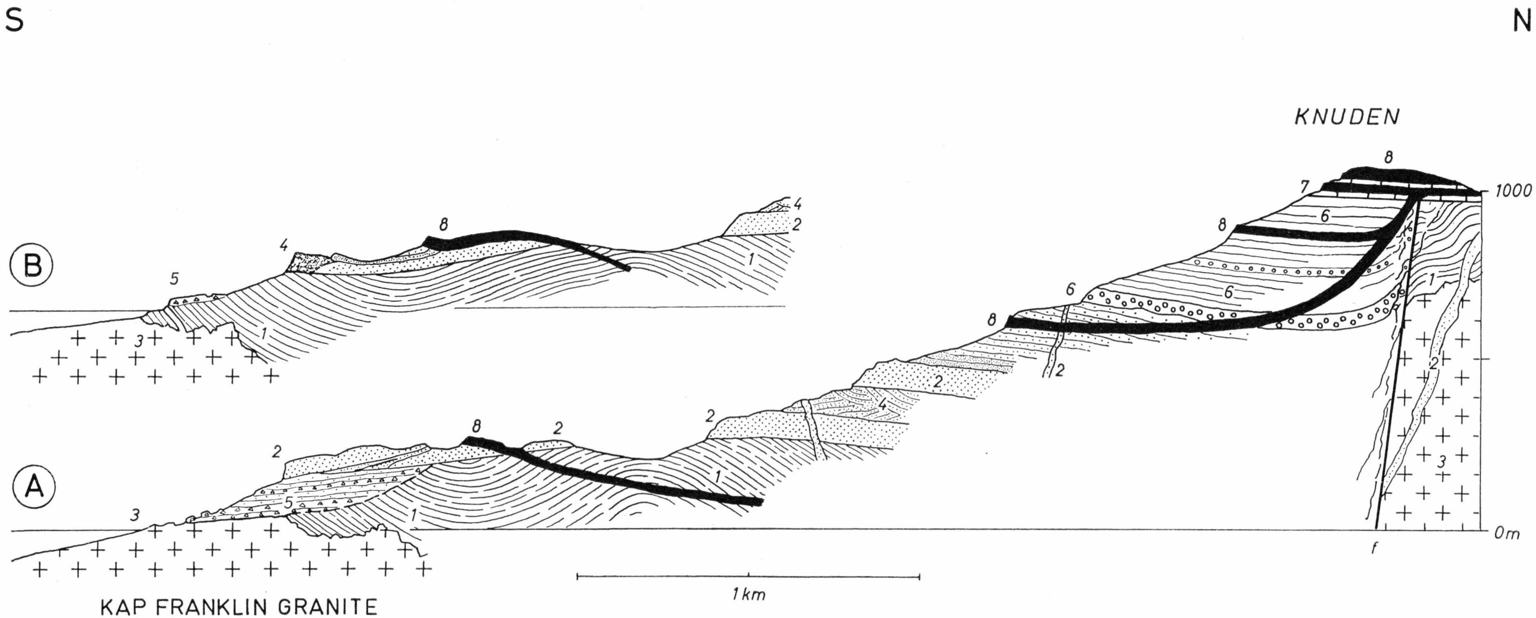


Fig. 14. Sections showing the stratigraphical position of the Middle Devonian Kap Franklin Granite. Sections A and B cut the southern slope of Knuden about 3 and 3.5 km, respectively, to the west of Kap Franklin.

Pre-granite formation: (1) Vilddal Series (Middle Devonian greyish-green sandstone beds of at least 1,500 m thickness).—(3) *Kap Franklin Granite* (post-tectonic batholith which invaded the folded Vilddal Series. Sample KF-111-182 derives from the compartment north of the pre-Permian fault "f").—*Post-granite formations:* (2) quartz porphyries, (4) accumulation of mostly rounded porphyry blocks, tuffs, and tuffites, (5) breccias, conglomerates, and fluvial sandstones of the Kap Franklin Series (Middle Devonian); (6) conglomerates and sandstones of the Randböl Series (Middle Devonian).—(7) Upper Permian and Eotriassic beds, (8) Tertiary basalts.—After H. Bütler (1954, fig. 15, p. 72).

an incontestable sequence of incidents based on stratigraphical facts. Bütler (1940, p. 23; 1957, pp. 12–15; 1959, pp. 179–182) recognized *two Middle Devonian* (Hudson Land Phases I, II) and *two Upper Devonian spasms* (Hudson Land Phases III, IV).

As to the whole province, two differently directed movement patterns are discernible. The first, trending north-northwesterly, was apparently initiated before the second system which carries an east-northeast strike. The movements of both systems, however, overlap in time and are likely to be Middle and Upper Devonian in either case.

Both patterns bear the features of *superficial tectonics initiated by syntectonic off-shoots of granitic melts.* Over large sections there is an intimacy between folding, overthrusting, and intrusion of melt. The granites were intercalated conformably between the mechanically competent rocks. They form a principal ingredient of the young Caledonian structural make-up within Province (2). The granitic melts were intruded on the low-angle thrust planes and thus furthered the internal mobility of the growing thrust-fold belts. These *syntectonic granites* correspond to the ubiquitous late to post-orogenic type of granite in Central East Greenland, which is considered to be a late palingenetic product of the main orogeny (cf. Haller, 1955 b, p. 281). This statement of origin, however, applies to all the intrusive granites emplaced syn- or post-tectonically in the young Caledonian structural provinces. As indicated by the pattern of tectonics these granites crept into their places at different times, apparently launched by a forceful upward projection of molten material from squeezed reservoirs below the fluidal basal complexes.

Folds and forthrusts running north-northwesterly to northerly seem to represent the initial system of movements in the basin province (2). Its prevailing element forms a strip of mobility following the southern edge of the basin tract. In North Andrées Land and in Louise Boyds Land, sheets of intrusive granites are conformably and plastically involved in that folding, the front of which established a southwesterly directed thrust pattern. South of Kejser Franz Josephs Fjord, the folding runs co-axially to the old Caledonian superstructural upfolds, which were accentuated and partly overturned. On Ella Ø, the accentuation of the dominant anticline can be dated Middle Devonian based on stratigraphy. Notable strike-slip displacements with differential folding of the sides arose along former fault systems.

The pattern trending north-northwesterly shows furthermore in southern Bartholins Land, which is in the interior of the basin tract. There, a granite batholith about 30 km in length is emplaced in the elongation of an inferior flexure.

In Hudson Land, the elevation of thrust-wedges forced up by lateral pressure acting from southeast (Hudson Land Phase I, cf. BÜTLER, 1959, pp. 180–181) may coincide with the movements of this system.

The structural pattern trending east-northeasterly is presumably younger than described above. Its principal line marks a main morphological feature, *i. e.*, Hambergs Gletscher — Adolf Hoels Gletscher — Bartholins Land. The system cuts also through the southern high ground up to the innermost nunataks. It established a thrust-fold belt, 240 km in length, involving intrusive granites, which behaved syntectonically at the eastern flank and post-tectonically at the western flank of the belt.

North of Waltershausen Gletscher, the thrust-fold pattern co-axially joins the stratigraphically dated thrust structures in Hudson Land (mainly Upper Devonian). In that area, an intensive faulting preceded the thrust movements. Thus, many of the former fault planes were overturned towards the west and developed into upthrusts[1]).

Isotopic Ages.—From Province (2) only the **Kap Franklin Granite,** mentioned above, was checked as to age (**395 ± 15 m.y.**). According to BÜTLER (1959, p. 181) the emplacement of that intrusive post-dates the structures initiated during the Hudson Land Phase I (Middle Devonian). As already shown, the strip of young Caledonian tectonism along the southern edge of the basin tract may be coeval with this phase of movements.

For future work on isotopic dating the widespread set of syn- and post-tectonic intrusives offers manifold possibilities to investigate that intricate pattern of movements, which are partly linked to stratigraphical evidence. This in turn may provide additional valuable calibration points in the Devonian Period for the geological time scale.

(3) Plutonic events of presumed Devonian age in the southern high ground.

The area of interest (3) extends from the inland ice to the coast. Liverpool Land displays the narrow eastern flank of that young Caledonian positive block. The geology of the Scoresby Sund region is only known in rough outline, so that the tectonic history of the region can be inferred only in general terms.

The southern tract consists nearly exclusively of segments of the *old Caledonian infrastructure*, consisting of reworked basement rocks. Parts of the *superstructure* find themselves merely in the edge zone to-

[1]) Cf. BÜTLER (1957, pp. 12–20, 74, pl. I; 1959, pp. 179–182, pl. IV), HALLER (1961 b, pp. 182–184).

wards the down-flexed basin tract (Suess Land, Lyells Land, Scoresby Land, and Canning Land) and in the nunatak zone. Devonian beds are absent in the whole area. The earliest post-orogenic formations are considered to be Carboniferous (viz. "Rødeø Conglomerates" in the inner Scoresby Sund, cf. Bütler, 1957, p. 59).

On the whole the southern high ground was a *resistance area* in young Caledonian time. Folding and upthrusting acting from northeast affected the tract only along its edge between 72° and 74° N. Lat.

In the region of Scoresby Sund there is no light concerning the extent of the young Caledonian movements yet. There too, several post-metamorphic shear planes were noted.

It has been concluded that big granite batholiths of late Caledonian age broke through the interior of this area. The intrusions are placed on two lineaments striking north-northeasterly in a remarkable manner: (i) The batholith in *Charcots Land* (longitudinal axis 40 km) and the narrow batholith *Nordenskjölds Gletscher* (longitudinal axis 60 km) set the first alignment. (ii) The second line parallels the latter. It consists of a fairly continuous batholithic invasion of 150 km that extends from the *Staunings Alper* to *Renland.*

As it had been determined in the Staunings Alper (cf. Haller, 1958, pp. 95–100, 142) these batholiths developed at intervals.

It seems likely that the act of granite intrusion partly coincides with the tectonic events in the Old Red basin. Suitable isotopic ages could give a definitive answer to this problem.

Minor Succeeding Episodes.

(Upper Paleozoic movements affecting the Old Red basin).

In Upper Paleozoic time, *shallow disturbances* affected the Old Red basin of Central East Greenland. Bütler (1955, p. 11) declares them to be *trailers of the Caledonian orogeny.* They merely touch the Caledonian pattern temporally as well as spatially. Two separate phases of movements can be distinguished.

(a) The early Carboniferous movements, called "*Ymers Ø Phase*"[1]), produced open N.-S. folds within the molasse basin between Ymers Ø and Kong Oscars Fjord. The warpings flatten in the north of Kejser Franz Josephs Fjord. The southern area underwent stronger distortion. In the western part of Geographical Society Ø and Traill Ø crowded folds partly occur in a thrust pattern. An upthrust towards the west establishes the western edge of the affected area. There is a general association of that shallow tectonism with displacement of fault blocks, denudation, and the accumulation of the continental Middle Carboniferous.

[1]) Cf. Bütler (1955; 1959, p. 182).

(b) On the south side of Kong Oscars Fjord warpings about northeasterly axes affected the Upper Carboniferous strata, which are unconformably overlain by coarse detritus of (Lower?) Permian age. Movements responsible for these structures are styled "*Scoresby Land Phase*"[1]).

The Geological Time Scale tentatively applied to the Paleozoic Orogenic Cycle in East Greenland.

On the basis of the above-mentioned data on the absolute age as well as of the hitherto available data on the standard time scale (Kulp, 1961) the time indices of the Paleozoic orogenic cycle in East Greenland are probably as the following:

(3) Minor succeeding episodes:	350 to 270 m.y. (Carboniferous)
(2) Late Caledonian spasms:	400 to 350 m.y. (Devonian)
(1) Caledonian main orogeny:	420 to 400 m.y. (Silurian).

This tentative scale outlines an astonishing longevity of the sequence of tectonic unrest. Yet the major orogeny with vast regional metamorphism was probably restricted to the Silurian. The *main orogeny* launched by deep-seated mobility along the whole east coast, from at least 70° to 82° N. Lat., reached its climax in the end of the Silurian, and probably even lasted till the earliest Devonian. This short and violent *growth of the principal belt* contrasts with the long-enduring orogenic decline which caused several secondary foci of tectonic activity between 72° and 76° N. Lat. Later secondary pulses continued for 100 m.y. until the entire belt was completely stabilized and finally relaxation set in.

The secondary *late spasms*, were generally observed to produce folding related to regional compression and the upward injection of late-orogenic palingenites. In each case the area was quite restricted compared with that of the main orogeny. These late-tectonic events arose during the Devonian, over an interval of about 20–50 m.y.

The tectonic events called *minor succeeding episodes*, which occurred during the Upper Paleozoic, were controlled by the destruction of the Siluro-Devonian mountain ranges by block faulting and related crustal movements. Warping and thrusting, partly launched by lateral pressure acting from the east, occurred in an area strictly confined to the southern compartment of the Old Red basin structure.

[1]) Cf. Bütler (1935 b, p. 31), Witzig (1954, p. 16), Haller (1961 b, p. 185).

4. Post-Caledonian Block Faulting.

In post-Devonian periods several late Caledonian fracture systems were renewed at different times:

(1) First of all, strong faulting was operative in the *Carboniferous*, as mentioned above. Its dominant systems strike N.-S.

(2) Later on, during the *Mesozoic* and the *Cenozoic*, vertical displacement combined with tilting of fault-blocks acted in a recurrent manner. Especially in the early Tertiary many of the existing N.-S. fault lines revived and new systems, mainly diagonal faults, developed. The step-like fault block arrangement generally descends towards the east. In Central East Greenland, the prevailing pattern affected the outer fjord region only (cf. Fig. 15). Its faults and flexures are linked to extensive basaltic eruptions, which occurred in several generations (cf. Wenk, 1961 a, b).

The reader will find details concerning that post-Caledonian fracturing mainly in the papers of Koch (1929, I; 1930, 1935), Vischer (1943), and Bütler (1957).

Thus, from Scoresby Sund (69° N. Lat.) to Kronprins Christian Land (82° N. Lat.) a basic pattern of fracturing exists along the actual edge of the continent. Systems of multiple, high-angle faults running near N.-S. essentially led to the present-day coastline.

5. Cenozoic Disturbances.

As discussed above, the southern edge of the Paleozoic *North Greenland* fold belt contains a superimposed thrust-fold pattern of presumably Cenozoic age.

In *East Greenland*, weak superficial folding of post-Mesozoic age is to be found (a) coastwise in the region between 80° and 83° N. Lat., and (b) in the coast area of Central East Greenland between 71°30′ and 72° N. Lat.

(a) In *Northeast Greenland* shallow folding affected northeastern Kronprins Christian Land, and the eastmost part of Peary Land as well.

In *Kronprins Christian Land*, post-Caledonian cover rocks (Carboniferous, Permian, Triassic(?), and presumably Cretaceous or Tertiary beds) were subjected to NNW.-SSE. warping (cf. Nielsen, 1941, p. 18). The crest-lines of the broad saddles run at a distance of about 25 km. In the environs east of Station Nord, Haller recognized upthrusting towards southwest, which may be also related to that folding. Likewise

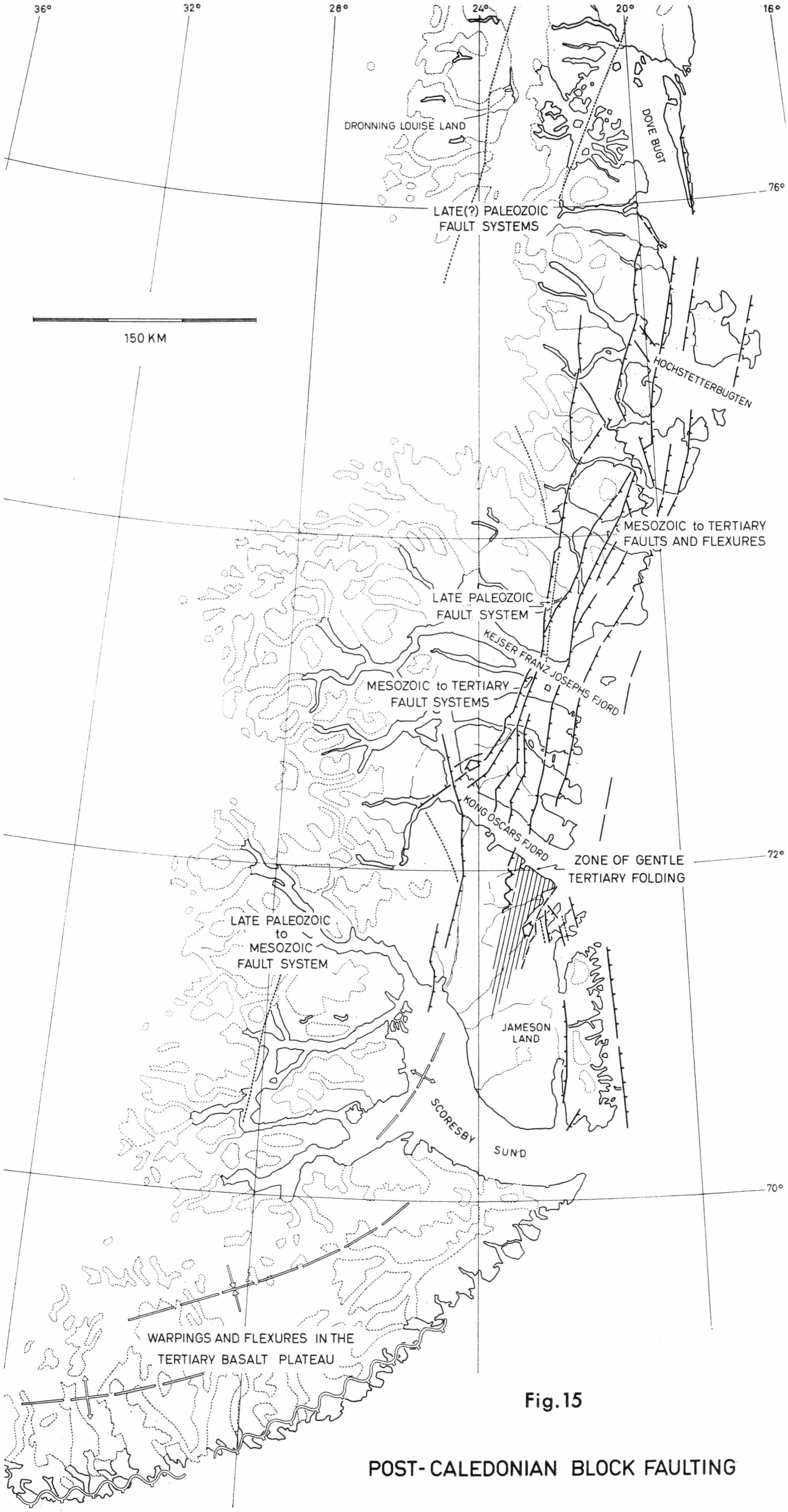


Fig. 15

POST-CALEDONIAN BLOCK FAULTING

it seems possible that strike-slip displacements along post-Caledonian NE.-SW. faults in southern Kronprins Christian Land are linked to those Cenozoic disturbances. Moreover, warping about northwesterly to north-northwesterly trending axes occurs on the oblong islands to the northwest of Station Nord. That structure pattern is supposed to continue to the *easternmost Peary Land*, from where similar structures have been reported.

(b) In *Central East Greenland*, a shallow folding of post-basaltic age, *i. e.*, Cenozoic, is observable in eastern *Jameson Land*, as mentioned by Rosenkrantz (1929, p. 149), Noe-Nygaard (1934, p. 76), and Trümpy and Grasmück (1962). The production of those open folds trending near N.-S. was apparently launched by vertical displacement of fault blocks.

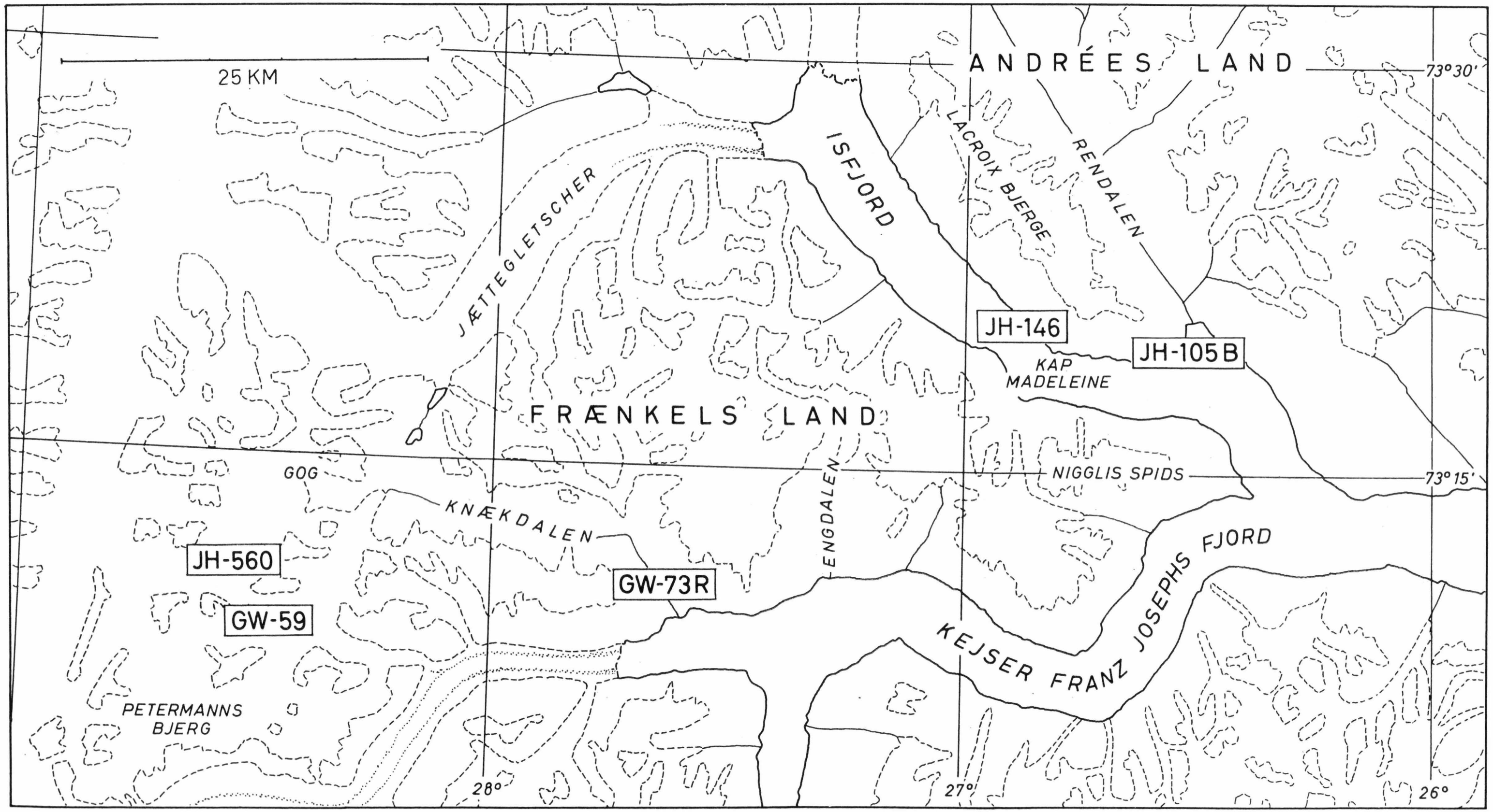


Fig. 16. Location of samples in the region of inner Kejser Franz Josephs Fjord.

POSTSCRIPT

While this paper was in press, at Columbia University additional data from East Greenland samples have been obtained. Sample locations are shown in Figure 16. The analytical data are given in Tables 3 and 4.

Table 3. Additional Results of K^{40}-Ar^{40} Measurements on Samples from the Kejser Franz Josephs Fjord Region.

Sample	*% K*	*Ar^{40*} scc/g*	*Isotopic Age (m.y.)*
GW-73 R Muscovite	6.74	1.23×10^{-4}	410
JH-146 Biotite	7.29	1.27×10^{-4}	395

Table 4. Result of a Rb^{87}-Sr^{87} Measurement on Sample GAA-135 from the Basement Exposure in the Innermost Scoresby Sund Region.

Sample	*Rb ppm.*	*Sr^{87*} ppm.*	*Isotopic Age (m.y.)*
GAA-135	455	4.41	2290

Sample GW-73 R (Coll. E. Wenk, 1951)

Locality: *Fraenkels Land* (73°11′ N/27°40′ W). Mouth of Knækdalen.

Geological Setting: Caledonian metamorphite of sedimentary origin. Sample GW-73 R represents a band of mica-schist which is involved in the main orogenic infrastructure (migmatite sheet "Hagar", see Figure 9).

Petrography: Schistose variety of *staurolite-garnet-biotite-muscovite-plagioclase-gneiss.*

References: Wenk and Haller (1953) pp. 27–31, pls. I, II; Schwander (1953), pp. 283–85, 289; Wenk (1954) pp. 309–12; Haller (1955a) pls. I, II.

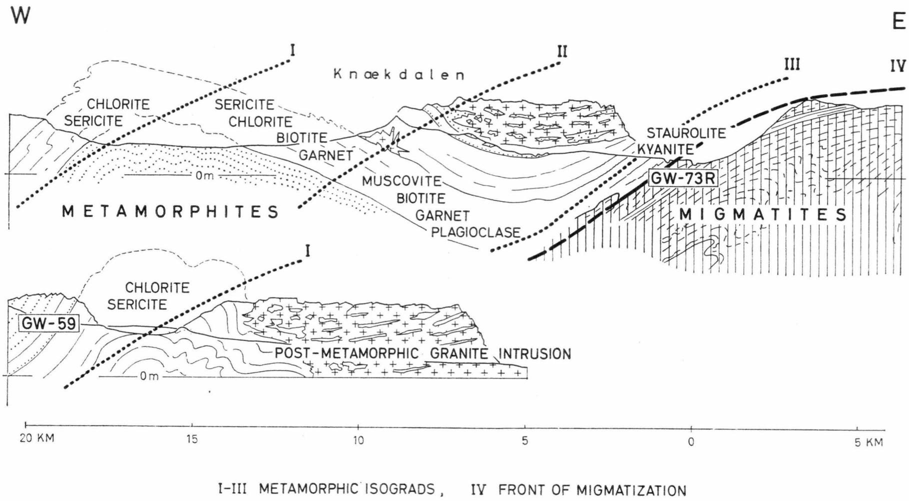


Fig. 17. Root zone of migmatite sheet "Hagar", showing location of Sample GW-73 R.

Discussion. – As shown in Figure 9, at the head of Kejser Franz Josephs Fjord, progressive stages of the main Caledonian metamorphism are to be found over a horizontal distance of 20 km. Eleonore Bay Group phyllites outside this aureole of regional metamorphism yielded isotopic ages of 425 m. y. (JH–560) and 410 m. y. (GW–59). In addition to these determinations, Sample GW-73 R represents a band of a pelitic metasediment inside the migmatite body, which welled as a tongue into the superstructure (Figure 17).

As it is to be seen on Figures 9 and 17, the zones of equal mineral facies cut across the stratification and across the fold-structures. The fabric of the metamorphic sediments shows that porphyroblasts were formed partly during partly after the folding. This, together with the cross-cutting of the isogrades, indicates that the heat operation outlasted the process of infrastructural doming. The welling-up of that centre of migmatization caused the folding as well as the heat operation far into the superstructure.

In contrary to other compartments of the old Caledonian infrastructure (*e. g.* "Migmatite Dome Nigglis Spids"), in the root zone of "Migmatite Sheet Hagar" from where Sample GW-73 R derives, no post-tectonic pegmatite invasion is known. Therefore, the mica age of Sample GW-73 R (**410 ± 10 m.y.**) is probably a fairly reliable date for the **climax** of the **Caledonian main orogeny** in Central East Greenland.

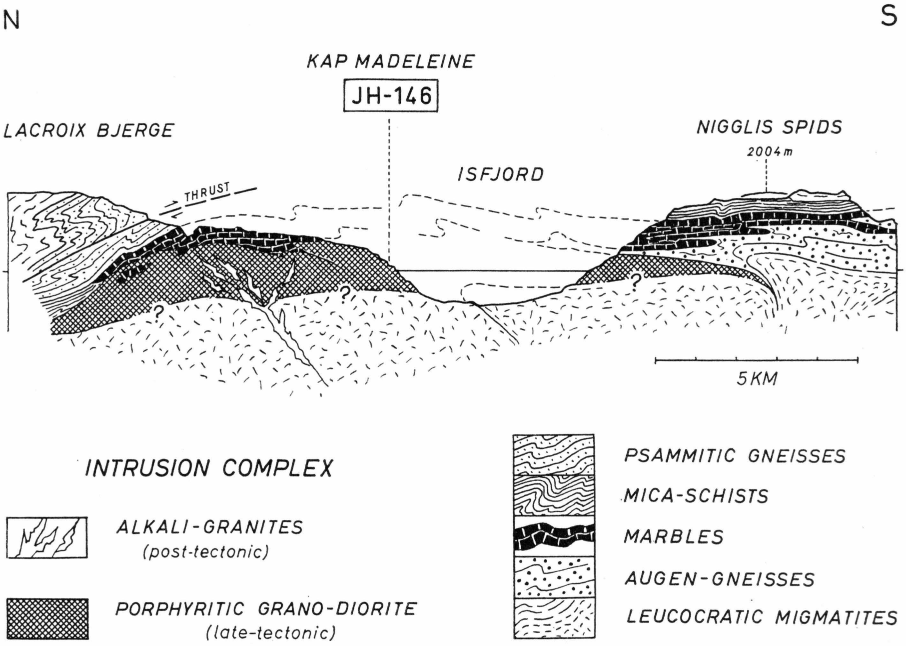


Fig. 18. Geological section across the Kap Madeleine grano-diorite complex in Isfjord. – After J. Haller (1955 a) pl. III.

Sample JH-146 (Coll. J. Haller, 1950)

Locality:	Western *Andrées Land* (73°20′ N/26°50′ W), Isfjord, Kap Madeleine.
Geological Setting:	Caledonian intrusive complex which mainly consists of a porphyritic grano-diorite with lenses of hornblende-biotite-schists. The complex occupies the core of an anticline in the northwestern flank of "Migmatite Dome Nigglis Spids", see Figure 18. The emplacement developed in steps the earliest of which are closely related to the upwarping of the migmatite dome (main orogeny). The latest intrusions are post-tectonic.
Petrography:	Coarse-grained, mesocratic *hornblende-biotite-grano-diorite* with phenocrysts of *micro-perthite* (up to 6 cm in length). The rock bears epidote-zoisite, titanite, spinel, apatite, and calcite.
References:	Haller (1953) pp. 79–93, pls. I, II, VI; (1955 a) pp. 76–77, pls. I, II, III.

Discussion. – The bulk of the grano-diorite complex is mainly of replacement-origin. The rock-types formed during the late stage of the infrastructural doming are shown on Figure 19. The predominant type, represented by Sample JH-146, is the *porphyritic grano-diorite* (1). It

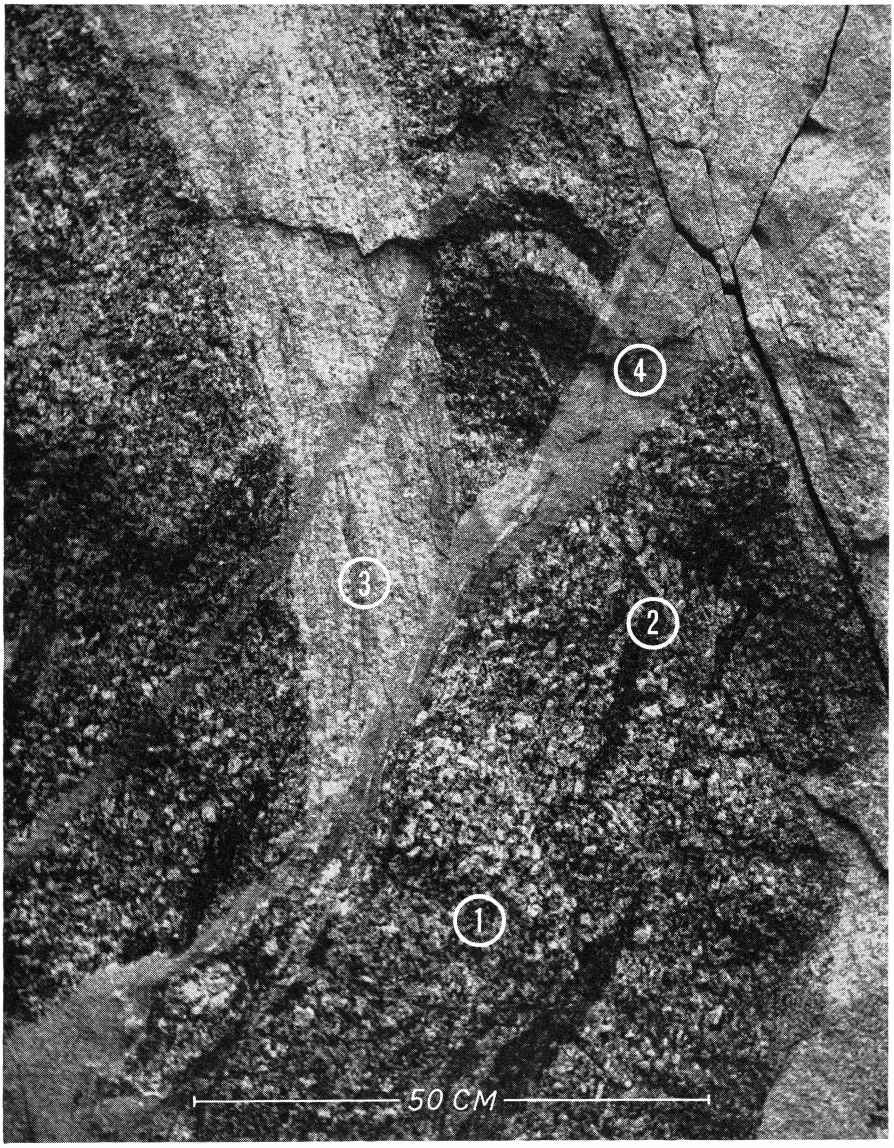


Fig. 19. Porphyritic grano-diorite complex of Kap Madeleine. (For explanation, see text).

is crammed with xenoliths (2) of *hornblende-biotite-schists* which are remnants of the replaced host-rock. The introduced material is represented by a heterogenous alkali-feldspar *pegmatite* (3), and an *aplite* (4) of alkali-granitic composition. These veins were intruded largely contemporaneously.

The biotite of Sample JH-146 was formed during this intricate process of aplitic-pegmatitic veining and replacement.

At a later stage, the congealed grano-diorite complex was partially subjected to invasion of *albite-ric hliquids* and *aqueo-igneous fusion.* (Cf. HALLER, 1953, pp. 89–91).

The mica age of Sample JH-146 (**395** ± **10 m.y.**) suggests either that the formation of the grano-diorite complex is related in time to the late orogenic intrusives (see pages 56–57) or, more likely, that the complex was sufficiently warm at the time of this subsequent invasion of liquids to have caused loss of radiogenic argon.

APPENDIX

Some Remarks on the Terminology "Caledonian".

According to its temporal position the initial and most intense orogenic happenings in East Greenland have to be defined as **Caledonian.** As indicated by the present isotopic ages as well as by the stratigraphical record in Northeast Greenland, it is a matter of fact that as to its age the main orogeny corresponds to the Caledonian in its best sense, that is the "Caledonian *sensu stricto*" (STILLE, 1919, p. 201) which established the Lower Paleozoic folded belt in Caledonia[1]), *i. e.* Scotland, (KULP, *et. al.*, 1960).

Nevertheless, in the progress of investigation the team of geologists, who explored the East Greenland belt under the leadership of Dr. Lauge Koch, decided to style the East Greenland orogeny "Caledonian *sensu lato*"[2]). For it has been very useful to use a term, which is suitable to a whole sequence of *Lower Paleozoic*[3]) *tectonism.* Though within the structural pattern of the entire East Greenland fold belt there is a striking dominance of the main orogenic architecture, the additional disturbances, caused by late tectonic spasms in Middle, and Upper Devonian times, must be genetically related and incorporated into the Caledonian drama. Thus, the concept of the "Caledonian *sensu lato*" applies to the main act as well as to all subsequently developed Devonian structures which were controlled by the arrangement of the principal architecture.

This terminology, however, is in accordance with the best STILLEan practice (STILLE, 1924). For he comments as to the orogenic events acting during Devonian time:

'In Europa bezeichnen wir als "*kaledonisch*" jene Faltungen, die insbesondere im Norden gewirkt und hier das System der "Kaledoniden" geschaffen haben. Die Faltung erreichte, wie wir sahen mit dem Ausgang des Silurs ihr Ende. Demgegenüber sind "*variscisch*" jene jüngeren Faltungsphasen, die das System der Varisciden südlich der Kaledoniden aufbauten. Sie haben *nach* der Devonzeit oder frühestens im Spätdevon eingesetzt.'

1) Cf. SUESS, Ed. (1888, p. 100).

2) Cf. HALLER (1955 a, pp. 42, 160), FRÄNKL (1956, p. 7), KOCH (1961, p. 153).

3) The *Lower Paleozoic* includes Cambrian, Ordovician, Silurian, and Devonian.

'Nun ist aber die *zeitliche Trennung zwischen kaledonischer und variscischer Faltung* deswegen etwas *unsicher*, weil auch im Devon, auch abgesehen vom spätesten Devon, Orogenesen nachweisbar sind, . . . Es erhebt sich die Frage, ob man sie als kaledonische Nachläufer oder als variscische Vorläufer ansehen soll.

In Einzelfällen ist die Entscheidung dieser Frage wohl zu treffen. So mag man die . . . *Faltungen im schottischen Devon*, als im Bereich der Kaledoniden liegend, als *Ausklang der kaledonischen Faltung* betrachten. Dagegen wird man in den . . . schwachen unterdevonischen tektonischen Bewegungen im Unterharz ebensogut einen Nachklang der dort erkennbaren kaledonischen Vorgänge, wie einen Vorläufer der variscischen Faltung erblicken. Die Trennung wird eben dann schwierig, wenn es sich um Gebiete mit sowohl kaledonischer wie variscischer Faltung handelt und die ganze variscische Faltung schliesslich ein Fortgang der kaledonischen ist.' (op. cit., pp. 77–78).

The conception proposed by KOCH and co-worker, moreover, is in agreement with the more recent terminologies of UMBGROVE (1947), RUTTEN (1949), and DE SITTER (1956):

UMBGROVE (op. cit. p. 27) underlined that 'as more and more facts came to light it became clear that Lower Paleozoic or "*Caledonian belts*" had not all originated during the same period.' On his tabular statement (op. cit. p. 28) as well as on his world-map showing fold belts established during "Caledonian epochs of compression" (op. cit. pl. 1), he applies the term "Caledonian" to an interval of time ranging from the Cambrian to the Upper Devonian, that is the entire Lower Paleozoic era. His arguments are the following:

'Though the *oldest epoch* in a so-called "Caledonian" belt is as a rule the Taconic, and the youngest the Erian or Mid-Devonian far more ancient Cambrian phases seem to occur in Asia. The oldest movements in Australia (Cambrian and Ordovician) were likewise regarded by Andrews[1]) as Caledonian epochs, and the *youngest epochs* in this "Caledonian" sector were observed to occur towards the close of the Devonian (the Bretonic epoch appearing elsewhere as the oldest in Variscian folded chains).' (Op. cit. p. 27).

RUTTEN's critical examination of STILLE's theory of short, worldwide, and synchronous orogenetic phases, alternating with long anorogenic periods has aimed at a destruction of that 'building STILLE and his followers have erected' (RUTTEN, 1949, p. 1757). He showed that 'the facts are not in accordance with this theory' because 'orogenetic periods occur irregularly, at quite different dates in different regions'. 'Moreover an orogenetic period is not of a very short duration. Much of the evidence used by STILLE is unreliable, consisting of inexact or uncritical age determinations.' (Op. cit. p. 1755).

Concerning STILLE's "Caledonian *sensu stricto*" RUTTEN emphasized: 'The terms Ardennic and Eric ought to be suppressed, because we are

[1]) ANDREWS, E. C., *The structural history of Australia during the Paleozoic.* J. Proc. Roy. Soc. (New S. Wales), *71*, (1938).

only able to distinguish movements belonging to a *Neosilurian* phase. *No definite age* can be given for these orogenics' (op. cit. pp. 1759–60). As to that point, however, STILLE himself revised his former statement when he wrote (1950, p. 227):

> 'Nachstehend wird also, wie ich schon länger getan habe, nur noch von einer *einzigen* jungkaledonischen [=Caledonian *sensu stricto*] Faltung gesprochen. Will man für sie neben der Bezeichnung "jungkaledonisch" noch eine der anderen Bezeichnungen beibehalten, so müsste aus Prioritätsgründen "ardennisch"[1]) den Vorzug vor "erisch" haben'.

The foregoing quotation from STILLE's comprehensive review of the Caledonian structures in Mid-Europe leads to the discussion about another nomenclatural point:

The use of "old" and "young" in the Caledonian terminology of East Greenland. As to the well proven tectonic sequence in East Greenland in BÜTLER's and HALLER's practice)[2], the term "*old* Caledonian" corresponds to the main orogeny while "*young* or *late* Caledonian" is applied to the late orogenic spasms of Devonian age.

Considering the classic terms "*alt*kaledonisch" and "*jung*kaledonisch" styled by STILLE (1919, p. 201; 1924, p. 64) our application of *old* and *young* differs somewhat.

As long as the main orogeny in East Greenland was supposed to be pre-Silurian (Taconic) our "old Caledonian" was in essential agreement with the classic term, that refers to Ordovician movements. Having come to the conclusion that the East Greenland main orogeny is Silurian in age we actually should avoid any further application of "old Caledonian" in East Greenland.

Nevertheless, it seems that there are reasonable grounds to continue this practice. With reference to the passage above, quoted from RUTTEN (1949), it seems that the last four decennia should have taught us that a tectonic sequence within an orogenic cycle is regionally controlled by its environmental settings and not by any correlative rhythm. Thus, the classic terms "alt-" and "jungkaledonisch" have lost their character as a time-marker. They should no longer be applied to long-range correlations as originally thought by STILLE.

The terms "*old*" and "*young*" Caledonian should be freed from any definite temporal position so that they can be *used as an adjunct to explain a relative stage of tectonic development* within the Caledonian do-

[1]) According to GOSSOLET's term "*Ridement des Ardennes*", cf. GOSSOLET, J., *L'Ardenne.* Mém. Carte géol. Fr. (1888).

[2]) BÜTLER (1935 a, *et sqq.*), HALLER (1956 a, *et sqq.*).

main. The East Greenlandian practice, however, finds like-minded authors among the British geologists, such as M. and A. G. MACGREGOR (1948, p. 5), who also contrast Old Red tectonics with *old* Caledonian structures (which were initiated towards the end of the Silurian, being "jungkaledonisch" in STILLEan practice).

Moreover, BÜTLER (1954, p. 121) drew a parallel between the late orogenic spasms of Devonian age in Greenland with the *Acadian* folding processes of the Appalachians. In the present-day view, however, it seems not suitable to apply correlative sub-terms to stages of the development of a fold belt, which is as far away from the type locality as the one of East Greenland. In addition to this, the tectonic sequences in the Appalachians and in the East Greenland fold belt are different in many respects.

The setting of the Upper Paleozoic disturbances within the Old Red basin. The shallow tectonism which affected the southern portion of the Old Red basin is, by no means, of the size of an actual orogenic system. This merely represents succeeding episodes within a system of intramontane basins which were filled up with Old Red and partly with Carboniferous detritus[1]).

It appears that even the thrust-fold pattern established during the *Ymers Ø phase* reflects a gravitational tectonism initially launched by post-orogenic fracturing and formation of northerly trending horst elements, as it had been vaguely outlined by NOE-NYGAARD (1934, p. 70).

In regard to the tectonic aspect, in his first papers dealing with the Devonian of East Greenland, BÜTLER (1935 a, b) interpreted that Ymers Ø folding as a "posthume kaledonische Bewegung" (1935 b, p. 25), and he pointed out that 'these *late-Caledonian* folding movements in Devonian times continued through part of Carboniferous times' (1935 a, p. 32). With respect to the papers of KOCH (1929, 1931, 1935), FREBOLD (1932), NOE-NYGAARD (1934), and others who paralleled that latest stage of Caledonian manifestation with STILLE's *Variscian folding phases*[2]) BÜTLER (1935 a, p. 20), wrote:

> 'It has turned out, however, that the tectonics of the region, especially in the deeper Devonian series, are much more complicated than assumed, and *that the tectonic development of East Greenland has been very different from that assumed according to* STILLE's *scale*.'

[1]) In Central East Greenland, the continental Carboniferous as well as the coarse clastic Lower (?) Permian deposits are still to be considered waste products ("molasse") of the Caledonides, which were only peneplaned when the area became a part of the Upper Permian sea.

[2]) See quotation from STILLE (1924) on page 68.

Likewise KOCH (1935) had some reservations as to the general setting of the Variscian disturbances in East Greenland when he introduced his passage dealing with that tectonism as follows:

'Über die variszische Tektonik besteht noch keine völlige Klarheit, und es ist möglich, dass die bisher vertretenen Anschauungen über Art und Ausmass der variszischen Bewegungen korrigiert werden müssen.' (op. cit. p. 139).

Nevertheless, BÜTLER entitled his paper (1955), which mainly dealt with the Lower Carboniferous tectonism on Ymers Ø, Geographical Society Ø, and Traill Ø "Das *variscisch* gefaltete Devon zwischen ...", and he advocated the term "Variscian orogenic phase" with reference to the age and the areal distribution of these movements (op. cit. pp. 11–12, 123).

In regard to the *temporal position of the Ymers Ø phase*, BÜTLER and the authors mentioned above were doubtless correct when they called the Lower Carboniferous tectonism "Variscian" and even when they compared it with the "Sudetic phase"[1]) which is the widespread and most intense Variscian orogenic action in Central Europe in the Upper Paleozoic. But considering the *geotectonic aspects* as well as the East Greenland fold belt as a whole, *the term "Variscian" leads to some misunderstanding*, and it is of importance to give a short statement on that point. If we accept the current view of the development of an orogenic cycle, which is in its fundamental concept still based on HALL's principle, we have to remember that the principal orogenic belts, caused by deep-seated mobility, in most cases raised along geosynclinal tracts. Hence, an orogenetically deformed crustal segment had been usually subjected first to geosynclinal conditions, or it had been at least a part of a marine depositional area. In regard to this criterion or to that of deep-seated mobility, neither in the East Greenland fold belt nor in one of the other circum-Scandic belts traces of a fundamental Upper Paleozoic orogeny are ascertainable.

Consider the geological setting of the *authentic Variscian* orogenesis, that affected *Central Europe* mainly at the close of the Lower Carboniferous. There, the Upper Paleozoic tectonism acted within a substantial geosyncline, that was filled up by a vast sequence of *marine Devonian*, which indicates a deep-water facies. Towards the north, that geosynclinal depression was bounded by the Caledonian domain which is characterized by continental to epicontinental Devonian accumulations, which are called the Old Red[2]).

As already vaguely stated by STILLE (1924; see quotation on page

[1]) Cf. STILLE (1924, p. 82).

[2]) Cf. GIGNOUX (1955, p. 108), BRINKMANN (1959, p. 79), etc.

69) and later on definitely underlined by UMBGROVE (1947, pp. 27–29) it is a matter of fact that *Caledonian and Variscian epochs overlap.*

In places the two orogenic patterns can actually be found side by side or crossing each other so that a proper Variscian pattern is superimposed on former Caledonian tectonics, as it is supposed to be in several districts in Mid-Europe[1]). A conclusive example, moreover, is Sardinia[2]) in the Mediterranean region.

In other orogenic belts, as for example in the Appalachians[3]) or in the Innuitian System[4]) there is a prolonged series of movements, being of Early, Middle, and Late Paleozoic age. There, it would seem unreasonable to force a terminology designed for the European setting upon those orogenic systems. Thus, these terms are avoided in regard to the Paleozoic orogeny in *North Greenland* also.

Considering the East Greenland fold belt, which is an integral part of the circum-Scandic Caledonian domain, the term "Variscian" should be omitted altogether, as it is misleading from the point of view of the structural development of that area.

[1]) Viz. *Ardennes*, *Rhenish Schiefergebirge*, *Sudetes*, etc., as stated by STILLE (1951), KETTNER (1956) and others.

[2]) In *Sardinia* movements referred to the Caledonian orogeny acted towards the close of the Cambrian and lasted into the Ordovician ("Sardic phase", STILLE, 1939). As recently shown by VARDABASSO (1956), the Sardic Caledonian orogeny was preceded by the formation of a "geosynclinal" tract in Cambrian time, and the Caledonian-deformed compartment, again, became a part of a Siluro-Devonian geosyncline which was affected by an intense Variscian orogenesis in Carboniferous time.

[3]) Cf. KING (1959, pp. 42, 66).

[4]) Cf. THORSTEINSSON and TOZER (1960, pp. 6–11).

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Færdig fra trykkeriet den 8. august 1962.

PLATES

Plate I.

Aerial view of Paul Stern Land and Vestfjord Gletscher taken in eastward direction towards Vestfjord (left) and Gaaseland with Gnejssö in the background on the right. The granite Sample GAA-135 (K-Ar mica 1900 $\pm$ 50 m.y., Rb-Sr microcline 2300 $\pm$ 50 m.y.) of the *Precambrian basement* (A) derives from the southern promontory of Paul Stern Land, seen in the centre of the plate.

The *basal psephitic series* (Ps) of the Precambrian geosynclinal sequence (Eleonore Bay beds) accumulated on an irregular relief; it is conformably overlain by the *marble-chlorite-phyllite series* (M). The *phyllite-mica schist series* (Ph) shows an inverted succession of metamorphic zones (cf. page 23).

This plate is reproduced from the paper of E. WENK (1961 b, Plate VI).

Geodætisk Institut Eneret, Nr. 651-J/12,084.

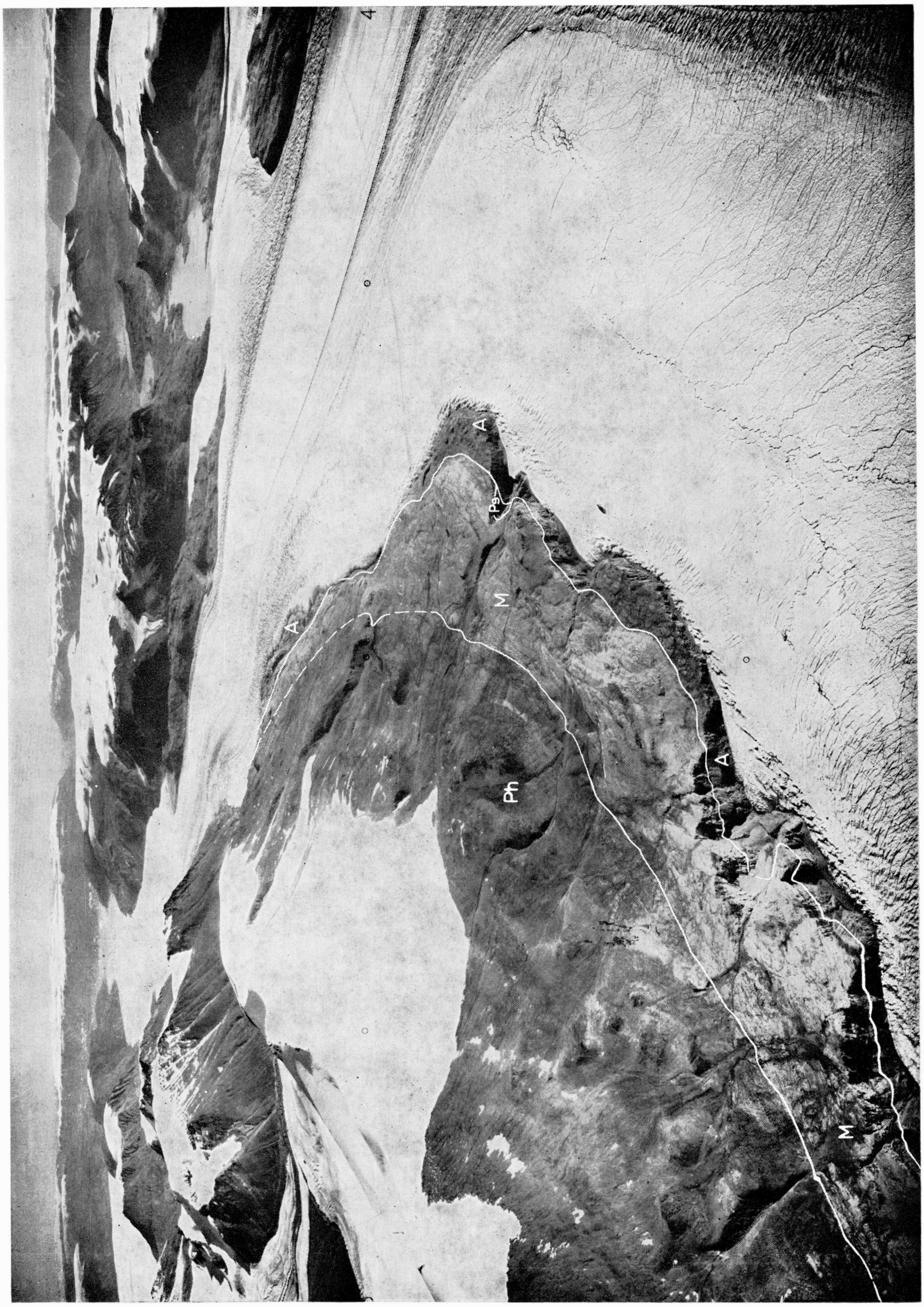
A
Ps
M
A
Ph
A
M

Plate II.

The photograph shows the polymetamorphic migmatite HN-89 from Grandjeans Fjord. It represents ancient crystalline incorporated in the Caledonian infrastructure of the main orogeny, when it was folded about north-northeast axes. In young Caledonian time the gneissose area was reheated and refolded in a transverse direction. During this second Caledonian reactivation the migmatites returned to a macroplastic state which gave rise to large-scale flow structures. In detail the gneissose material remained also rigid in part and then became boudinage-like or cut into shear lenticles, the scars of which became obliterated by increasing effect of quartzo-feldspatic mobilizers.

Plate III.

Core and outer part of migmatite dome "Nigglis Spids" exposed on the south wall of Jomsborg. The vertical cliff is 1800 m in height. Behind to the right is Renbugten.

The white migmatites (C) emerging in the core are of monzonitic to granitic composition; they are of replacement origin and include bands and lenses of paraschists such as the *phlogopite-diopside-schist* JH-105 B. The basal migmatites are covered by a shell of dark-coloured hornblende-rich rocks (Ga) about 50 m in thickness. This basic seam grades upwards into augengneisses (E). This latter rocks form several tongue-shaped sheets which are separated by mica-schists (J) and some marbles (H). On the ice-covered top to the left, metamorphic quartzites (K) rest upon a flat thrust plane (dash-dot line). The migmatite dome is crossed by many post-tectonic pegmatites (P). The photograph of Figure 10 was taken from the position of "P", the upper right corner of this plate.

 PLATE III.

Plate IV.

Structure Map of the East Greenland Fold Belt, 1:2,000,000.


EAST GREENLAND FOLD BELT
STRUCTURE MAP
COMPILED BY
JOHN HALLER
1 : 2,000,000
0 20 40 60 80 100 KM
EXPLANATION
CENOZOIC
PLATEAU BASALT
ACID ERUPTIVES
SEDIMENTS
DISTURBANCES
ANTICLINE
SYNCLINE
THRUST PLANE
MESOZOIC and LATE-PALEOZOIC
POST-DEVONIAN SEDIMENTS
PALEOZOIC
MINOR SUCCEEDING EPISODES
ANTICLINE
SYNCLINE
direction
hade
OVERTHRUST
UPPER PALEOZOIC 350-270 M.Y.
YOUNG-CALEDONIAN FOLDING
FLEXURE
ANTICLINE
SYNCLINE
OVERTHRUST
SUPERFICIAL TECTONICS
ANTICLINE
plunge
SYNCLINE
DEEP-SEATED TECTONICS
DEVONIAN 400-350 M.Y.
OLD-CALEDONIAN FOLDING
ANTICLINE
SYNCLINE
OVERTHRUST
SUPER-STRUCTURE
ANTICLINE
SYNCLINE
INFRA-STRUCTURE
SILURIAN 420-400 M.Y.
EARLY PALEOZOIC IN THE FORELAND
PRECAMBRIAN
'HAGEN FJORD GROUP' IN THE FORELAND
CAROLINIDIAN FOLDING
A S SUPERSTRUCTURE
A S INFRASTRUCTURE
'THULE GROUP' IN THE FORELAND
PRE-GREENLANDIAN BASEMENT (NOT AFFECTED BY OROGENY)
Topography after USAF Aeronautical Chart Service
PEARY LAND
INDEPENDENCE FJORD
HAGEN FJORD
DANMARK FJORD
Station Nord
KRONPRINS CHRISTIAN LAND
INGOLF FJ.
LAMBERT LD.
TUBORG FONDETS LAND
JÖKELBUGT
SKÆRFJORDEN
GERMANIA LAND
Danmarkshavn
DRONNING LOUISE LAND
DOVE BUGT
STORE KOLDEWEY Ø
BESSELS FJ.
SHANNON Ø
GRANDJEANS FJ.
PAYERS LD.
CLAVERING Ø
HUDSON LD.
ANDREES LD.
BOYDS LD.
Hambergs Gl.
MOSKUSOKSEFJORD
KEJSER FRANZ JOSEPHS FJORD
Kap Franklin
YMERS Ø
SUESS LD.
GEOGR. SOC. Ø
TRAILL Ø
LYELLS LD.
KONG OSCARS FJORD
SCORESBY LD.
Mesters Vig
STAUNING ALPER
CHARCOT LD.
CANNING LD.
JAMESON LAND
LIVERPOOL LAND
RENLAND
SCORESBY SUND
GAASELAND
GREENLAND
400 KM
82°
81°
80°
79°
78°
77°
76°
75°
74°
73°
72°
71°
70°
36°
32°
28°
24°
20°
16°
12°