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TECTONIC MAP OF EAST GREENLAND (1:500,000)

AN ACCOUNT OF TECTONISM, PLUTONISM, AND VOLCANISM IN EAST GREENLAND

BY

JOHN HALLER

WITH 83 FIGURES AND 2 TABLES IN THE TEXT
46 PLATES AND 3 MAP SHEETS

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Abstract

Greenland is bounded to the north and east by Paleozoic orogenic belts. The *East Greenland fold belt*, part of the circum-Scandic Caledonian domain, runs parallel to the coast line and is exposed from 70° to 82° N. Map sheets 1–3 cover the belt and adjoining foreland parts north of the 72nd rarallel, *i.e.* over a length of 1,100 km.

In Northeast Greenland, there are relics of a north-northwesterly trending Precambrian fold belt, the CAROLINIDES. This orogeny followed the deposition of the Precambrian *Thule Group*, that then covered most of North Greenland. Throughout late Precambrian and Lower Paleozoic times, the Carolinidian belt remained a positive element separating the geosyncline of Central East Greenland from smaller depositional basins in Northeast Greenland. The latter included the late Precambrian *Hagen Fjord Group* and a marine succession of *Cambro-Silurian* age.

In the geosyncline of Central East Greenland, more than 16,000 m of beds accumulated, some 13,000 m in the late (?) Precambrian (*Eleonore Bay Group*, *Tillite Group*) and 3,000 m in *Cambro-Ordovician* times.

The East Greenland CALEDONIDES developed during three distinct periods of tectonic activity which formed an unbroken sequence in the orogenic cycle: The *main orogeny* (old Caledonian), caused by deep-seated mobility, occurred in the late Silurian and/or earliest Devonian and affected the whole length of the east coast north of the 70th parallel. In Northeast Greenland, a marginal thrust belt outlines the western edge of this principal structure pattern. Regional metamorphism and igneous activity were most intense in the region between lats. 70° and 76°, *i.e.* the realm of the Central East Greenland geosyncline. This region also became the site of all *late orogenic activity* (young Caledonian), including the formation of an intramontane molasse basin (more than 7,000 m of Middle and Upper Devonian red beds). In those highlands *minor folding and thrusting* lasted until the Lower Carboniferous. In the northern part of the Caledonian belt, tectonic unrest ended much earlier and incursions of the sea began in Carboniferous time (Moscovian). In the southern region, which was then still the site of continental deposition, clastic beds of Upper Carboniferous and Lower Permian age accumulated in fault-bounded troughs indicating a compound rift system.

The western flank of this late Paleozoic rift system remained henceforth positive and, therefore, part of the continent. But the area to the east subsided to become part of the Upper Permian sea. This incursion re-established the marine regime over wide areas that had been land since the Caledonian mountains emerged. A fluctuating shelf-sea persisted there throughout the *Mesozoic*. The basement underlying this shelf gradually was broken off into a complex pattern of *antithetic fault blocks*. Northerly running fault block structures characterize all of the coast north of Scoresby Sund (70° N). To the south, however, the coastal structure is quite different and also of later date. There, some 7,000 m of basalt lavas (*Brito-Arctic province*) erupted after Central East Greenland had become the site of regional upwarping at the very end of the Mesozoic. Except for a few flows, all lavas cooled on dry land. The building

up of the *basalt plateau* was accompanied by gentle subsidence, and when the major volcanicity ceased, the plateau sank below sea-level. In Neogene times, differential vertical displacement then caused the present inland area to rise (resulting in the highest mountains in Greenland, *viz.* up to 3,700 m around the 69th parallel), while in the coastal area the plateau was submerged in the Denmark Strait. Between these areas of opposed displacement the Paleogene lava pile was bent into a giant flexure. Although this *crustal warp* (of some 8 km relative vertical displacement) has no direct bearing on the structures exposed on the mainland farther north, it is vital to the understanding of Greenland's southeast coast and, moreover, provides a link to the structural history of Iceland and the North Atlantic.

PREFACE

It is difficult to characterize those features which set apart a "tectonic" map from other maps presenting geological data. Anyone agrees that a *geological map* ought to represent the broad variety of rocks displayed at the surface of the earth. Sedimentary rocks are differentiated as to their age, related to a time-clock based on the pulsatory evolution of our animal's life. Metamorphic, plutonic and volcanic rocks are distinguished as to their petrological characteristics, that is in terms of their mineral assemblages. A good geological map becomes an index of exposed rock units expressed in terms of their biostratigraphy, lithology, and petrology. The revealed pattern of boundaries separating mappable rock groups and also the shapes of outcrops, controlled by the intersection of geological boundaries with topographic contours yield, in addition, a two-dimensional representation of the crustal architecture as it shows up at the surface of the earth.

In areas of complicated structure, the predominant structural elements such as faults and folds or mesoscopic planar and linear structural features may be gathered in a *structure map*. This type of map is likewise an index, assembling geometrical data. A structure map, as a rule, is a supplement to the geological map. In a similar way do *structure sections* complete the standard of geological documentation of the area concerned. The construction of structure sections, however, already involves a good deal of interpretation; based on features observed at the surface one aims to extrapolate downwards into the crust. In mountainous regions, but especially in areas deeply intersected by steep-sided glacial valleys—such as the fjord system of Central East Greenland—rather accurate cross-sections can be obtained. They are extremely valuable and add to the two-dimensional map the third dimension. Finally, a combination of geological maps and structure sections leads to the construction of *block-diagrams* showing the distribution of rock groups in space.

Yet the fourth dimension—time—is scarcely and only indirectly shown on conventional geological maps and diagrams. It is the goal of the *tectonic map* to reveal the pattern of earth history in space and time. With this in mind it becomes evident that the tectonic map schedules

the time events and characteristics of the *crustal drama*—to use the Termiers' theatrical title[1]). The acts of the drama are clearly distinguishable by a grouping of major structural elements and by assembling units of sediments controlled by the same tectonic environment. A tectonic map may be of continent-wide scope and include first-order tectonic features or it may be restricted to a smaller area and depict second-order tectonic features such as faults, folds, structural contours, and the like[2]). The tectonic map is a synthesis of stratigraphy, petrology and structure, stressing the time-space relationship of the rock material making up the crustal segment concerned. Therefore, major subdivisions shown on a geological map will disappear, while tiny spots may become the foothold of ambitious boundary lines. On the one hand, this synthesis requires abstraction and simplification, on the other hand considerable interpretation must be included. In places, the tectonic maps tends to become an "interpretative diagram", which, although including much factual material, goes much further in portraying inferred relationships than would be allowed in a geological map. Admittedly, the impression of completeness may insinuate even where knowledge is meager. The distinction between the factual presentation of the geological map and the interpretative portrayal of the tectonic map is analogous to that between photograph and abstract portrait; the geological map may be thought of as an aerial photograph with hand-colored rock units but the tectonic map represents an abstract portrait revealing both the sequence and character of earth movements through time.

Although standard symbols have been reasonably established for most sorts of structural elements, the implication of colored patterns varies greatly among tectonic maps according to the structural peculiarities of the different regions. There are no generally agreed specifications for the use of colors, and their choice and implication is found to be guided not at the least by technical considerations. Confronted with the wide range of choice in the matter of technical methods, my conception of presenting East Greenland was certainly influenced by the "Tectonic Map of the United States", on a scale of 1:2,500,000, first published in 1944 by C. R. LONGWELL *et al.* This admirable piece of compilatory work—the result of innumerable conferences and exchanges of views—became widely accepted as a successful prototype and its specifications were largely retained for the improved new edition of 1961. However,

[1]) H. and G. TERMIER (1958). The Geological Drama, Hutchinson and Co., (London).

[2]) Cf. PH. B. KING (1964). Tectonic Map of North America. Intern. Geol. Congr. XXII Sess., Report to the Commission for the Geological Map of the World. U. S. Geol. Survey, (Washington, D. C.).

as admitted by LONGWELL[3]), the creators of the United States tectonic map evidently received their principal ideas from EMILE ARGAND's magnificent structural map of Eurasia presented at the International Geological Congress at Brussels in 1922.

The East Greenland map, in showing a region some 1,000 km in length, differs in scale and purpose from the transcontinental prototype. Also, the present map focuses attention on the structural history of one orogenic belt, *i.e.* the East Greenland Caledonides. Thus, for instance with regard to the post-Caledonian history of the region, the map is rather incomplete owing to lack of sub-surface data on the attitude of the major truncation planes. It would have been very instructive to furnish the Mesozoic fault blocks of the outer coast with structural contours as well. But our research carried out in a remote region and in the face of unfavorable climatic conditions could by no means reach that mature stage of completeness. Moreover, it was beyond the scope of the expedition work to accumulate data for that purpose. Our efforts were concentrated on surface geology and within this we aimed at a completion of the geological mapping, including stratigraphical, petrological and structural studies.

We have to picture that at the time LAUGE KOCH's first East Greenland Expedition started work in 1926, many fjords were still unknown and a great part of the mountain scenery was unexplored. Therefore, within the scope of geological reconnaissance work topographic mapping was launched as well, particularly by LAUGE KOCH who himself had already completed tremendous cartographic work in North Greenland[4]). From the beginning of his East Greenland Survey, LAUGE KOCH stressed geological mapping as being the main purpose of his expedition. As early as 1929, in his "Geology of East Greenland" he published a colored outline map on a scale of 1:1,000,000 showing the geology between Scoresby Sund (70° N) and Danmarkshavn (77° N).

Decisive progress in the mapping program, however, could only be made when, in the early thirties, the Geodetic Institute, Copenhagen, joined KOCH's organization with an intensified terrestrial and aerial survey. The Danish research was purposefully accelerated by the dispute over the Norwegian annexation of a prominent part[5]) of Central East Greenland. The Danes resolved to affirm their sovereignty by publishing

[3]) C. R. LONGWELL (1944 a).

[4]) Topographic atlas of 24 sheets entitled "Map of North Greenland, scale 1:300,000, surveyed by LAUGE KOCH in the years 1917–23", published by the Geodetic Institute, Copenhagen in 1932.

[5]) *Erik Raudes Land* (Eric-the-Red Land), territory between 71°30′ and 75°40′ N. Lat.

a modern topographical map of the disputed area. Danish sovereignty over all of Greenland was finally endorsed by the International Court in the Hague on April 5, 1933. By a happy coincidence, the new map[6]) covered not only an area of political importance but it also included a vast number of excellent outcrops which were to prove to be the key to the geology of Central East Greenland.

In summer of 1936, preliminary prints of the topographic map were made available to KOCH's geologists and, with this, mapping was started on an accurate base. After World War II the work was continued systematically. In the field, mapping was carried out on a scale of 1:100,000, mainly focused on the publication scale of 1:250,000.

Having first joined the expedition in 1949, I started work in the Caledonian crystalline series of the inner Kejser Franz Josephs Fjord region. In 1952, after I had published my Ph.D. thesis on this subject, I became permanently employed on the expedition staff and as time went on, the compilatory work concerning the exploration of East Greenland became my responsibility. By courtesy of both the Greenland Department and Prof. Dr. E. WENK, head of the Mineralogical-Petrological Institute, University of Basel, I was able to carry out all the laboratory and paper work at my home in Switzerland. One of my jobs consisted of preparing the base maps for the printing of the "Geological Map of East Greenland 72–76 N. Lat" on a scale of 1:250,000, printed by the Geodetic Institute, Copenhagen, in 1965[7]). With this, a goal set by LAUGE KOCH in the early thirties was attained.

In the area north of the 76th parallel, where topographic maps comparable to those of Central East Greenland are still lacking, the geological investigations had more the character of reconnaissance than a systematic mapping. For this region as well as for the region south of the 72nd parallel, topographic base maps were obtained from the "WAC" edition[8]) on a scale of 1:1,000,000 and, in the early sixties, the "AMS" edition[8]) on a scale of 1:250,000 was used as a base for photogeological investigation.

The elaboration of a *tectonic map* of the East Greenland fold belt was actually not considered in the expedition's program. Yet while compiling geological maps of Central East Greenland on a scale of 1:250,000 and those covering Northeast Greenland on one-half or one-fourth that scale, I decided to systematically collect structural data as well. The present compilation started out from modest structure maps on a scale of 1:250,000 of small areas, such as my "Structure Map of

[6]) Cf. p. 19.
[7]) Cf. Medd. Grønland **183**.
[8]) Cf. p. 19.

West Andrées Land" (1953, pl. III), or that of the "Central Metamorphic Complex" (1955, pl. IV), followed by one showing the "Nunatakker Region" (1956a, pl. II). With these plates I acquired some experience in preparing multicolored line-cut prints. The plan of setting up a tectonic map, however, came into my mind only after the field studies, in the summer of 1955 when I was faced with several superimposed structure patterns in the fjord region between 74° and 78° N (1956c, fig. 2, pl. II). At that time, for laboratory use, I began to develop the style of map presented here. In the fall of 1959, Dr. KOCH asked me to contribute an "*Account of Caledonian Orogeny*" to the proceedings of the First International Symposium on Arctic Geology held in Calgary in January, 1960. Although I was forced to economize my time it seemed to me imperative to complete my contribution with a structure map showing the whole East Greenland fold belt. From the same draft, a reprint on a more suitable scale (1:2,000,000) was later published in Medd. Grønland (HALLER and KULP, 1962, pl. IV).

By the end of 1960, all sheets of the "Geological Map of East Greenland, 72–76 N. Lat." were finally turned in for printing and consequently I was able to tackle the compilation of the "Geological Map of Northeast Greenland", which will be published on a scale of 1:1,000,000. I have already remarked that in the northern part of the East Greenland fold belt systematic mapping was not yet possible. However, a number of restricted field trips were carried out by members of KOCH's expedition, but also other scientific groups[9]) contributed to the knowledge of this area. The scattered results were completed by making a large number of reconnaissance flights and spot landings in the summers of 1955, 1956, and 1958.

In 1960 and 1961, the aerial survey of the Geodetic Institute, Copenhagen, covered all North Greenland, including Kronprins Christian Land, by sets of overlapping air photographs on a scale of 1:50,000. By courtesy of the Geodetic Institute these sets were made available for photogeological studies and it is only through this additional work that a fairly complete outline of the Caledonian nappe structure of Kronprins Christian Land, first investigated by E. FRÄNKL in the summers of 1952 and 1953, could be obtained. After this study accurate structural data were at hand for the whole Caledonian belt north of the 72nd parallel, and early in 1962 I started the final draft of the present three map sheets (Fig. 1). Originally, a fourth sheet of similar size was also planned to

[9]) LOUISE A. BOYD's Arctic Expeditions 1937–38; Danish Expedition to Northeast Greenland 1938–39 (under the leadership of E. MUNCK and E. KNUTH); Danish Peary Land Expedition 1947–50 (led by E. KNUTH); British North Greenland Expedition 1952–54 (led by C. J.W. SIMPSON).

cover the Scoresby Sund area (70–72 N), but our investigations of this region were broken off in a state of preliminary mapping.

Although LAUGE KOCH's organization, under the auspices of the Greenland Department, ended its field-research in 1958, a financial grant was made towards the publication of the final results. Yet at the end of 1962, when Dr. KOCH retired, the financial backing through the Danish government expired and my incomplete maps lay fallow. As a Swiss scientist I am pleased to mention, that at this time I learned about the generosity of Swiss funds. In 1963, I received a joint maintenance grant from the "*Janggen-Pöhn-Stiftung*" (St. Gallen) and the "*Paul Niggli-Stiftung*" (Zürich). The purpose of this grant, however, was to subsidize the writing of a textbook on the "Geology of the East Greenland Caledonides"[10]); this book, of course, was closely related to the elaboration of the Tectonic Map, yet the finishing touch of the map drafting was only made possible in 1964 when the "*Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung*" awarded me a maintenance grant for the completion of the work initiated under the auspices of the Danish government. I am very grateful to these Swiss institutions; it was only through their backing that I was able to carry on my compilatory work at all. But I also wish to express my warmest thanks to the editors of "Meddelelser om Grønland" for their courtesy and support.

Faced with technical problems and decisions on the layout of the colors, the advice of Mr. G. HOLM-PETERSEN (Teknisk Afdeling, Geodætisk Institut, København) was very helpful. Close co-operation with the Danish institutions, however, was constantly facilitated by Miss INGRID BECK, who has taken care of all the publication work of LAUGE KOCH's team since 1945. I am indebted also to Mr. DOUGLAS RUMBLE (Harvard University) for editing work on the manuscript. As the preparation of these map sheets grew step by step in the course of nearly a decade I cannot mention all those who contributed to my work in the form of stimulating suggestions. Among them were certainly many of my colleagues in Switzerland but I also gained much stimulation from visits to Geology Departments in Great Britain, the Netherlands, and Scandinavia. While preparing the explanatory text, not at least, I made much use of the great experience of my colleagues in the United States. I should like to mention especially the co-operation with Dr. PHILIP B. KING (U. S. Geol. Survey) focusing around his recent compilation of the continent-wide tectonic map covering all North America on a scale of 1:5,000,000. Our exchange of views became extremely profitable to me

[10]) L. U. DE SITTER's Regional geology series, published by John Wiley and Sons, Ltd.

since we both had to tackle the East Greenland fold belt simultaneously but on two entirely different scales.

It is a pleasure to recall all the colleagues and friends who contributed to the finishing touch of this protracted work, yet my retrospect is overshadowed by sadness too as this day happens to be the second anniversary of Dr. LAUGE KOCH's death. He was, indeed, the outstanding promotor of all East Greenland geology.

Cambridge, Massachusetts
June 5, 1966

JOHN HALLER
Department of Geological Sciences
Harvard University

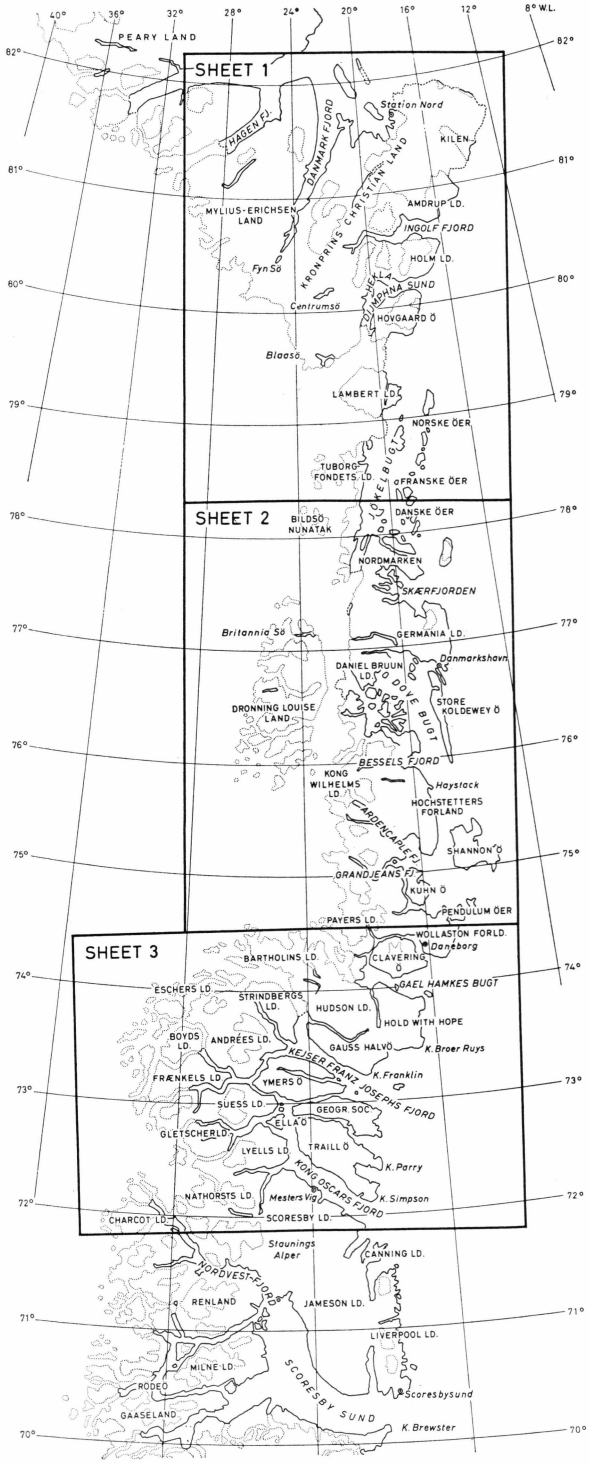


Fig. 1. Index-map showing layout of the Tectonic Map of East Greenland.

NOTES ON TOPOGRAPHY AND PLACE-NAMES

The outline of topography shown on the "Tectonic Map of East Greenland" were adapted from the Danish map series, on a scale of 1:250,000[11]), for the area between 72° and 76° N. Latitude; and from the United States Air Force "WAC"[12]) edition, on a scale of 1:1,000,000 and the United States Army's "AMS"[13]) series, on a scale of 1:250,000 for the area north of 76° N. The topography also includes improvements obtained during geological field work and by studies of some 40,000 aerial photographs.

The history of the exploration of East Greenland is recorded in the place-names applied by successive expeditions to the topographic features encountered by the explorers. Each expedition published its results as maps, printed in the native language of each party. A complete account of these expeditions and their work is beyond the scope of this note[14]); only a few expeditions and the place-names which they bestowed will be discussed here. Disregarding a dubious voyage made in the 14th century by two *Italian* brothers, the ZENOS, whose highly speculative map[15]) was incorporated in the maps and globes of the Flemish cartographers MERCATOR and ORTELIUS, the great *British* navigator HENRY HUDSON was probably the first to have sighted East Greenland's coast in 1607, during his exploration of the waters west of Spitsbergen. Following the edge of the pack-ice he discovered an island called "Hudson's Tutches"[16]) and then "*Hold with Hope*", a promontory at Greenland's

[11]) "Topografiske Kort Grønland", 1:250,000 (Fourteen sheets covering the area between 72° and 76° N. Lat. and one sheet of the outer part of Scoresby Sund), surveyed 1931–34 by the Geodetic Institute, Copenhagen, published in 1938.

[12]) "World Aeronautical Chart", 1:1,000,000, published by the U.S. Department of Commerce, Coast and Geodetic Survey, Washington, D.C.

[13]) "Army Map Service", U.S. Army, Corps of Engineers, Washington, D.C.

[14]) For cross-reference see W. H. HOBBS (1933), J. K. WRIGHT (1935), L. KOCH (1940).

[15]) NICCOLO and ANTONIO ZENO's map, published by their descendants in 1558. (See the presidential address by A. E. NORDENSKIÖLD (1883) to the Royal Swedish Academy of Science.)

[16]) This was soon rediscovered by a Dutchman, JAN MAY, and hence called *Jan Mayen*.

coast (74° N). HUDSON's successful voyage opened a new era of Arctic exploration: the "Whaling Period" of the 17th and 18th centuries, an enterprise dominated by Dutch expeditions. Whalers frequently approached East Greenland's coast but there are no accurate records of ships having entered the fjords. Yet names such as "*Land van Lambert*" (79° N), "*Baey door Gael Hamkes*" (74° N), and "*Land van Broer Ruys*" (73°30′ N) were given then.[17]) The Dutch naval activity expanding far into the arctic Atlantic was challenged by the British; there was much rivalry and competition. Finally, during the Napoleonic Wars, Dutch whaling industry was forcibly reduced by the continental blockade. It was then the priviledge of British whalers to carry on hunting and for the first half of the 19th century British voyagers promoted the exploration of the Northlands. Remarkable contributions to modern Arctic geography were made by the Scottish whaling captain WILLIAM SCORESBY, but particularly by his son WILLIAM, JR. In 1822, WILLIAM, SEN. explored the Scoresby Sund system (70° N) in quest of the mystic waterway across Greenland indicated on the ZENOS' map. At the same time WILLIAM JR. investigated the coast between 69° and 74° N.

One year after the SCOREBYS' success, Cpt. D. C. CLAVERING[18]) joined by Cpt. E. SABINE[19]) followed the same route through the pack-ice but pushed farther north in order to continue SABINE's research on the earth gravity and magnetism. A laboratory was established on "*Pendulum Island*" (74°30′ N). CLAVERING sailed to "*Shannon Island*" (75° N), but he also entered "*Gael Hamkes Bay*" (74° N), about which he had vague information from Dutch whaling reports. He went ashore at "Clavering Island" and was highly surprised to meet there a tribe of natives—the last Eskimos ever seen along the east coast north of the 66th parallel. For this reason no Eskimo place-names were to be adopted here in later years.

After a pause of half a century, East Greenland exploration revived through the ventures of the "*German North Pole Expedition* 1869–70". This expedition did not really reach its goal and one of its two ships was lost in the pack-ice. The more successful SS "*Germania*", under the command of Cpt. K. KOLDEWEY, reached SABINE's "*Pendulum Islands*",

[17]) Cf. G. AMDRUP (1913, p. 15).

[18]) D. C. CLAVERING (1830). Journal of a Voyage to Spitzbergen and the East Coast of Greenland, in His Majesty's Ship Griper. (Communicated by JAMES SMITH, Esq. of Jordanhill, F.R.S.E.; with a Chart of the Discoveries of Captains Clavering and Scoresby), pp. 1–30, The Edinburgh New Phil. Journ. **9**, (Edinburgh). (For reference see: Petermann's Geogr. Mitt. **16**, IX, pp. 320–29, Map pl. 21, (Gotha), 1870).

[19]) The British Captain SABINE of the Royal Artillery, the magnetic specialist on PARRY's Arctic expeditions, was the first to demonstrate the geographic correlation of magnetic declination.

where the party eventually had to winter. JULIUS V. PAYER, lieutenant of the Austro-Hungarian army, organized the expedition's sledge trips the first of which is traceable southward by place-names such as "*Ortler Spitze*" (Clavering Ø) and "*Tiroler Fjord*". In the spring, KOLDEWEY accompanied by PAYER and others marched with hand-sledges northwards across Dove Bugt and at the farthest point they reached on "*Germania Land*" (77°01′ N), they erected a cairn. The expedition sailed southwards that summer and entered "*Kaiser Franz Joseph Fjord*"; "*Eleonore Bai*" and "*Teufelschloss*" were named, and on August 12th, 1870, a three man party led by PAYER climbed a 2,100 meter high peak in the massif of "*Payer Spitze*". Far to the west they caught sight of a "gigantic pyramid of ice" which towered above the surrounding mountains. This was called "*Petermann Spitze*" after the organizer of the expedition, the famous geographer Dr. A. PETERMANN. The ascent of Payers Tinde was not only the first venture into the East Greenland coastal mountains but also the first big feat of mountaineering in the Arctic.

In the southeast of Greenland, Danish exploration started as early as 1828, when Lt. A. W. GRAAH's successful "umiak"[20]) expedition passed the southern tip of the Island and made the first contact with East Greenland's natives. In the seventies and eighties, again Danish Navy Officers, G. HOLM and T. V. GARDE, continued this effort and gained access to the Angmagssalik region, situated around the polar circle, where an insulated tribe of Eskimos—Stone Age people throughout—were discovered.

It was only in 1891–92 that a Danish Navy expedition, led by Dr. C. RYDER, advanced as far as Scoresby Sund in order to survey this widely ramifying fjord system.

In 1889, during a search for the missing balloon travellers ANDRÉE, FRAENKEL and STRINDBERG, the well organized Swedish expedition led by Prof. A. G. NATHORST mapped the Kejser Franz Josephs and "*Konung Oscars Fjord*" systems on a scale of 1:500,000[21]). This fairly reliable chart is furnished with quite a number of place-names, given by NATHORST's party. The names referred to expedition members or, as in the case of ELLA, RUTH and MARIA, to the expedition leader's wife and daughters respectively; all three representing picturesque islands in the center of the investigated area. But also the expedition's sponsors were considered, and from the list of gratuities it becomes obvious that the

[20]) *Umiak* is the Greenlander's skin boat worked by women; it used to be an important means of transportation on long hunting trips. Like the much smaller *kayak* it was made from driftwood and skin, but was unsafe in icechoked waters and rough weather.

[21]) A. G. NATHORST (1900).

more substantial the remittance the larger the fjord attached was, whereas the names of minor sponsors were related to capes and spits of lands only. NATHORST, however, did not attach his own name to a place, but to cheer his profession he called that fjord which showed the most beautifully colored rocks, "*Geologfjord*". NATHORST made, indeed, a number of important observations concerning East Greenland's geology, and by adapting the results previously obtained by the Germans in the north and the Danes in the south he compiled the first geological outline-map of the fjord region stretching from 70° to 76° N.[22])

At the very beginning of this century, another Danish expedition went to Scoresby Sund and Kong Oscar Fjord. Plans were also made to gain effective access to *Northeast Greenland.* The first advance into this remote part of Greenland had been made by ROBERT E. PEARY in 1892, by crossing the northern ice cap from Northwest Greenland to the head of what he then called the "*Independence Bay*" (82° N).

On June 24th, 1906, finally, aboard the SS "*Danmark*" one of the greatest Danish expeditions left Copenhagen. Its main object was to explore and map the unknown regions north of Kap Bismarck, which was reached by KOLDEWEY's party in 1870. It is true that, in 1905, the DUKE OF ORLÉANS had been ashore at places farther north, and from his ship "Belgica" had sketched the main features of the coast line almost as far as 79°30′ N; but from this place northward to PEARY's cairn the coast was entirely unexplored. The leader of this venture was the journalist and author L. MYLIUS-ERICHSEN. From the winter base *Danmarkshavn* (77° N) two groups of explorers travelled by dog-sledge northwards. One group, led by MYLIUS-ERICHSEN, mapped *Danmark Fjord* and part of *Independence Fjord*, but all died on the return journey. The second group, J. P. KOCH and ALFRED WEGENER, mapped the outer coast area and pushed to the north coast of *Peary Land.*

After the SS "Danmark" returned to Copenhagen plans were made to send out immediately another expedition to look for reports deposited by MYLIUS-ERICHSEN and his cartographer HØEG-HAGEN. This search led by Cpt. EJNAR MIKKELSEN was successful. In 1912, however, when MIKKELSEN was overdue, KNUD RASMUSSEN headed with a relief expedition—his "1st Thule Expedition"—eastward, largely retracing PEARY's inland ice route. The party entered the Danmark Fjord region through a valley called "Zig-Zag Dal" by PETER FREUCHEN, a well-known writer[23]), who then happened to act as cartographer.

In addition to coastal explorations, Danish parties went on to sledge widely across the inland ice. This is true for all the exploration of north-

[22]) A. G. NATHORST (1901).

[23]) PETER FREUCHEN (1935). Arctic Venture: Life in the Frozen North, pp. I–IX + 1–467, ill. (New York).

ern Greenland (RASMUSSEN's "2nd Thule Expedition" 1916–18[24]); LAUGE KOCH's "Bicentenary Expedition around North Greenland" 1920–23). A particularly remarkable inland ice journey—not made by dog-sledges but by Icelandic ponies[25])—was that of J. P. KOCH and A. WEGENER in April, 1913. This westbound expedition ascended the ice cap across *Dronning Louise Land*, a group of nunataks discovered by the "Danmark Expedition". The trail of this ride is unmistakeably marked by place-names such as "*Pony Gletscher*".

In the realm of the "Danmark Expedition", place-names were preferably referred to the Royal Danish family but also to the promotors and sponsors of the expedition[26]). Other names, however, such as "*Nioghalvfjerdsbræ*" become meaningful by translating (79th parallel Glacier)[27]).

The next great epoch of exploration—launched by E. MIKKELSEN's expedition to Scoresby Sund in 1924[28])—saw major activity in Central East Greenland where the Danes competed with Norwegians[29]) in carrying out geologic and topographic surveys. In the twenties also, French expeditions led by Prof. J. B. CHARCOT started work in Scoresby Sund. British parties under J. M. WORDIE investigated the geology of the Kejser Franz Josephs Fjord region, including an ascent of Petermanns Bjerg. In the thirties even two American expeditions[30]) contributed to the exploration of Central East Greenland. Yet the Danes' comprehensive survey directed by LAUGE KOCH dominated these activities.

In the summer of 1933, due to unusually favourable ice conditions, one of the expedition ships was able to push northward as far as Norske

[24]) On the "2nd Thule Expedition", PETER FREUCHEN was again in charge of cartography but severe disease caused him to stay at the winter quarters Kap York and the expedition's geologist, LAUGE KOCH, was entrusted with both cartographic and geologic exploration.

[25]) After SCOTT's tragedy, horseborne expeditions, were no longer sent to polar regions. In the thirties and forties, however, Icelandic ponies were frequently used by LAUGE KOCH's geologists in the lowlands of Central East Greenland, in particular for the transport of large slabs of rocks quarried by vertebrate paleontologists.

[26]) Cf. G. AMDRUP (1913).

[27]) Cf. list of place-names assembled by L. KOCH (1940, pp. 338–57).

[28]) In 1924, a voluntary "Scoresby Sound Committee" took the initiative to found a new settlement for East Greenlanders in this great fjord area, the one-time home of many Eskimos. One year later, the transfer of 82 persons was organized.

[29]) Norges Svalbard- og Ishavs-Undersøkelser, Oslo, "Karte von Nordostgrønland" (Blatt Claveringøya, Jordan Hill und Geographical Society-Øya) mit einem Geleitwort von O. LACMANN, (Justus Perthes, Gotha), 1937. [N.B. all place-names newly introduced on these topographic maps 1:100,000 were dropped by Danish authorities]. Report on the activities of Norges Svalbard- og Ishavs-Undersøkelser 1927–1936, pp. 1–125, 25 figs., 3 pls., Skr. Svalb. Ish. Nr. 73, (Oslo), 1937.

[30]) LOUISE A. BOYD's Arctic Expedition, 1933, and JOHN K. HOWARD's expedition to the fjord region of East Greenland in 1933.

Øer (79° N) whence LAUGE KOCH reached Kronprins Christian Land[31]) and the nunatak area to the south by aircraft. In May 1938, KOCH again touched this area on his reconnaissance flights made from Spitsbergen to Peary Land[32]). In the last pre-War season, however, the remoteness of the north was challenged once more by Danish dog-sledge parties[33])[34]) exploring mainly Kronprins Christian Land.

In Central East Greenland, cartographers and geologists promiscuously added new place-names to NATHORST's list. In the region between 72° and 74° N, in particular, Swiss geologists of KOCH's party adopted a number of place-names from Switzerland. Thus, names such as "*Schaffhauserdalen*" (Nathorsts Land) or that city's land-mark Munot in the form of "*Munotsbjerg*" (Ymers Ø) were obviously suggested by C. E. WEGMANN and H. BÜTLER; so also were names referring to masters of Alpine geology, such as *Argands* Gletscher (Lyells Land) and *Collets* Bjerg (Hudson Land) and the like. But many other names will remain obscure to the outsider. This is also true for various names suggested by geologists who carried out field-mapping after World War II. But there is no need, I feel, to reveal any more of the background of these names, since Prof. E. HOLTVED at the Geodetic Institute, Copenhagen, is in charge of filing a complete documentation of authorized place-names over Greenland.

In Northeast Greenland, *i.e.* north of Danmarkshavn (77° N), it became urgent to attach a number of names to places of particular geologic interest. The ones entrusted with this task, however, agreed to refer here mainly to the great venture carried out by members of the "Danmark Expedition".[35]) But exceptions were allowed as well, for instance in Dronning Louise Land place-names are easily traceable to British exploration carried out in the years 1952–54. Yet, the greatest man of this century could then only be honored in the form of a "*Winston Bjerg*", as by that time a rule was set by the approving Danish committee (Stednavneudvalget for Grønland) that full names of living persons could not any longer be related to new place-names.

As to principles of language, nowadays it has become an international

[31]) L. KOCH (1935 a).

[32]) Cf. L. KOCH (1940, pp. 300–337, pls. 12, 13, 21).

[33]) Dansk Nordøstgrønlands Ekspedition 1938–39. Udsendt af: ALF TROLLE, EBBE MUNCK og EIGIL KNUTH til Minde om Danmark-Ekspeditionen. Leaders: E. MUNCK and E. KNUTH. Cf. Medd. Grønland **126**.

[34]) Den Danske Hundeslæde-Ekspedition 1938–39. Leader: ELMAR DRASTRUP. Cf. Medd. Grønland **142**.

[35]) On the return of the expedition the artist painter ACHTON FRIIS presented a well illustrated, lively account of the voyage in his popular book entitled "Danmark-Ekspeditionen til Grønlands Nordøstkyst", pp. I–VI + 1–670, (Copenhagen), 1909.

agreement that geographical names should be given only with the approval of the recognized administrative authority and should be published in the language of that authority. In conformity with the resolution the "Stednavneudvalget for Grønland" adopted only names in either the Danish or Eskimo languages, and the authors of contributions to the "Meddelelser om Grønland" were requested to follow this principle strictly. Therefore on the *Tectonic Map* the correct Danish form is used throughout and the following list of English equivalents has been compiled for reference (Table I). I have to add, however, that many other names not indicated on the present map sheets, have been authorized as well.

Table I. *Index of Danish Words for the Place-Names.*

(In Danish the definite article is written as a suffix -en, -et, -ne, and is sometimes added to the proper name, such as *Fjorden.*)

Alper	=	Alps, rugged mountain area
Bjerg	=	mountain
Borg	=	castle
Bræ	=	glacier
Bugt	=	bay
Dal	=	valley
Dronning	=	Queen
Elv	=	river, stream
Fjeld	=	mountain, hill
Fjord	=	fiord, inlet, firth
Flade	=	plain
Flod	=	large river
Flyver	=	airman
Forland	=	foreland
Gaas	=	goose
Gletscher	=	glacier
Gnejs	=	gneiss
Graa	=	grey
Halvø	=	peninsula
Hare	=	hare
Havn	=	harbour
Hjørne	=	edge, corner, nook
Højland	=	highland
Horn	=	peak
Hvidbjørn	=	polar bear
Is	=	ice
Isstrøm	=	glacial stream
Jøkel (Icelandic)	=	glacier
Jomfru	=	virgin, maid
Kap	=	cape
Kejser	=	German Emperor, Kaiser
Kilde	=	spring, well

(continued)

Table I (cont.)

Kile	=	wedge(-shaped) (as in "Kiledal")
Knæk	=	with a sharp bend (as in "Knækdalen")
Kong	=	King
Klinter	=	cliff
Klippe	=	cliff
Kløft	=	cleft
Kronprins	=	Crown-Prince
Kyst	=	coast
maale	=	to measure (as in "Maalebjerg")
mørk	=	dark (as in "Mørkefjord")
Moskusokse	=	musk-ox
Næs	=	ness, point, promontory
Narhval	=	narwhal (as in "Narhvalsund")
Ö or Ø (Øer)	=	island(s)
Øst	=	east
Prins, Prinsesse	=	Prince, Princess
pynt	=	point, promontory
rød	=	red (as in "Rødeø")
Rype	=	white grouse
Sæl	=	seal (as in "Sælsøen")
Sø	=	lake
sort	=	black
Sne	=	snow
Spids	=	peak
stor	=	great (as in "Store Koldewey Ø")
Strædet	=	strait (as in "Danmarks Strædet")
spærre	=	to barricade (as in "Spærregletscher")
Sund	=	sound, strait
Syd	=	south
Taage	=	fog
Toppe	=	mountain, summit
Trold	=	goblin
Tvillingerne	=	twins
Ulve	=	wulf
Vest	=	west
Vig	=	small inlet

GEOLOGICAL SETTING OF THE MAP AREA

Around the north and east coasts of Greenland, Paleozoic fold belts envelope the stable Precambrian block of North America. The coastal fold belt of East Greenland is part of the circum-Scandic **Caledonides**; the belt of North Greenland belongs to the **Innuitian System** of Arctic Canada. Each of these fold belts forms a separate geological and physiographical entity (Fig. 2). On the mainland there is no connection between the two, neither structural nor morphological. It is true that in both cases the main movements took place in the Paleozoic, but their geosynclinal histories, their structures and phases of development are basically different. The main *folding* of the Caledonian System came in the late Silurian, while the movements which affected North Greenland and Ellesmere Island were Paleozoic and Cenozoic as well.

Both areas of deformation were already considerably eroded and peneplaned at the end of the Paleozoic. In spite of this, they form even today extensive mountain chains, due mainly to Mesozoic and Tertiary *block-faulting*. In both East and North Greenland, the young fractures follow, and at the same time accentuate, the strike direction of the Paleozoic structures. Along the east coast such a region of step-faulting occurs, the steps descending towards the Greenland Sea. On the north coast, a horst block forms the present-day mountain chain of North Peary Land. In both regions, the late-Paleozoic plane of erosion has been uplifted and dissected.

The old peneplain continues across the flat foreland region of the fold belt where it is preserved over wide areas. This intact **tableland** forms the third physiographic unit in Northeast Greenland. Structurally, it belongs to the Precambrian platform. Here, Precambrian and Lower Paleozoic beds sub-horizontally overlie the old gneiss basement. In Northeast and Central East Greenland, this basement is exposed in only a few places at the edge of the inland ice, such as in Tuborgfondets Land (78°40′ N), Bildsö Nunatakker (78°10′ N), Dronning Louise Land (76°–77°20′ N), and again in the very south, in Gaaseland (70°20′ N).

From Scoresby Sund (70° N) to Kronprins Christian Land (82° N), the Caledonian fold trunk forms a broad mountain wall. The 76th parallel divides this belt into two natural geological and orographical

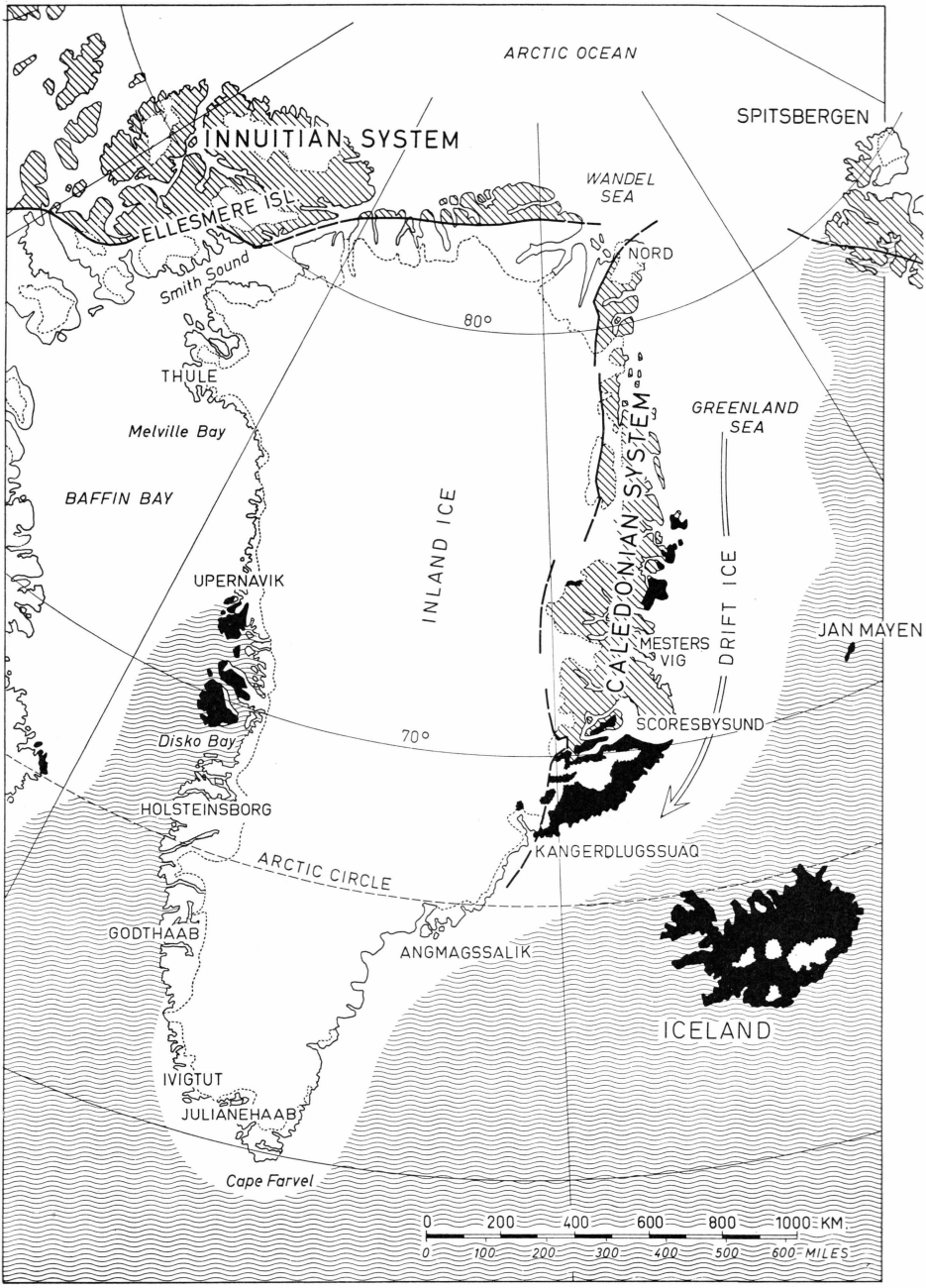


Fig. 2. Physiographic units of Greenland.

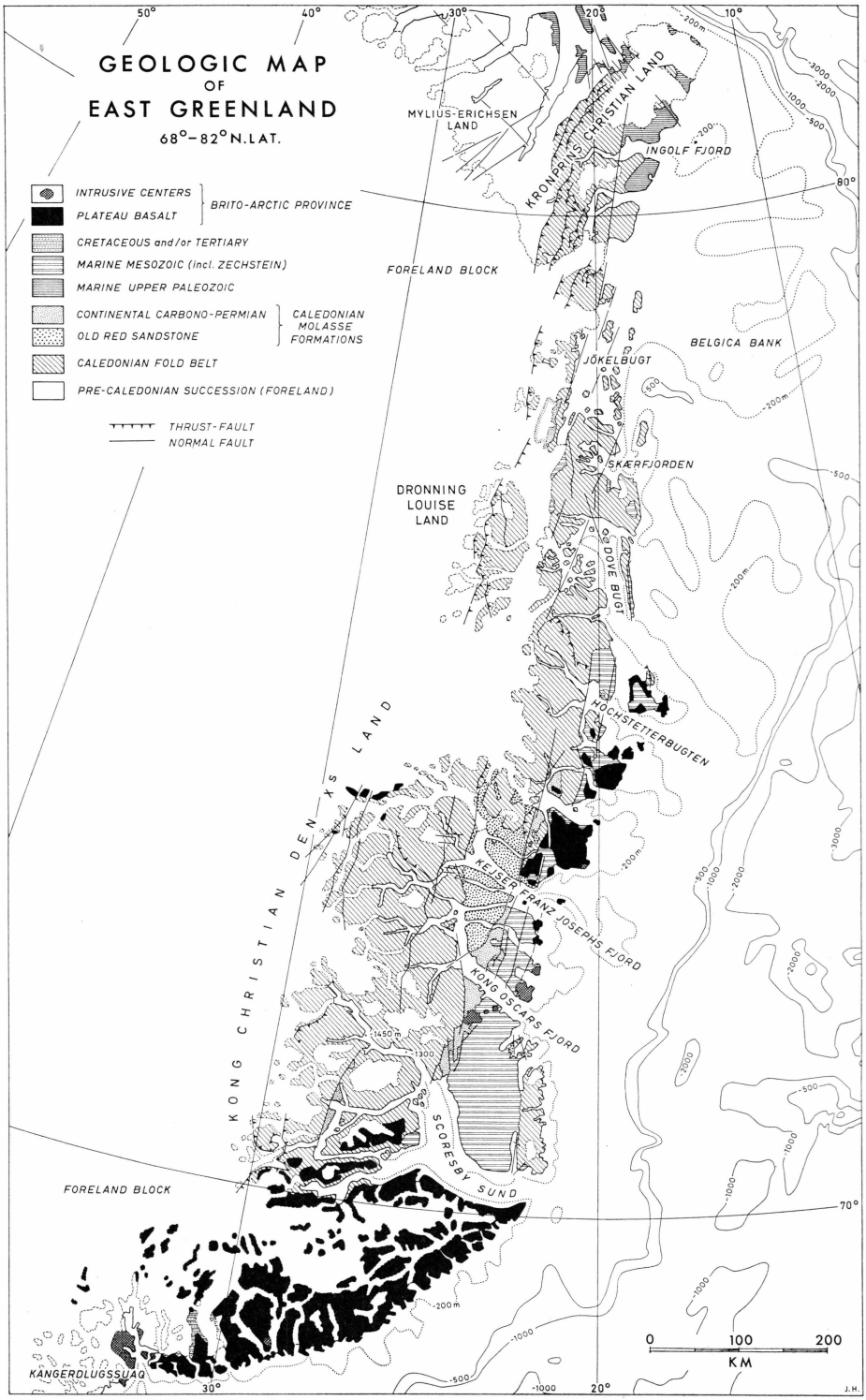

GEOLOGIC MAP
OF
EAST GREENLAND
68°–82° N.LAT.
INTRUSIVE CENTERS
PLATEAU BASALT
BRITO-ARCTIC PROVINCE
CRETACEOUS and/or TERTIARY
MARINE MESOZOIC (incl. ZECHSTEIN)
MARINE UPPER PALEOZOIC
CONTINENTAL CARBONO-PERMIAN
OLD RED SANDSTONE
CALEDONIAN MOLASSE FORMATIONS
CALEDONIAN FOLD BELT
PRE-CALEDONIAN SUCCESSION (FORELAND)
THRUST-FAULT
NORMAL FAULT
MYLIUS-ERICHSEN LAND
KRONPRINS CHRISTIAN LAND
INGOLF FJORD
FORELAND BLOCK
BELGICA BANK
JÖKELBUGT
SKÆRFJORDEN
DRONNING LOUISE LAND
DOVE BUGT
HOCHSTETTERBUGTEN
KEJSER FRANZ JOSEPHS FJORD
KONG OSCARS FJORD
KONG CHRISTIAN DENS LAND
SCORESBY SUND
FORELAND BLOCK
KANGERDLUGSSUAQ
0 100 200
KM
J.H.

Fig. 3.

parts. The structure and shape of the mountains are different to the north and to the south of this line (Fig. 3). The diversity of development corresponds to a tendency which can be traced far back into pre-Caledonian history.

North of the 76th parallel, in *Northeast Greenland* the Caledonian structures clearly show a movement direction towards the west; folding and thrusting are here manifestations of the main orogenic activity. Along this coastal section, remnants of a late Precambrian fold belt, the "Carolinides", which was caught up in the Caledonian movements, are also found. In the west, the edge of the Caledonian belt and the foreland are exposed. Post-Caledonian sedimentary cover rocks are almost entirely confined to northern Kronprins Christian Land; Tertiary igneous rocks do not occur north of the 76th parallel.

To the south of this line, in *Central East Greenland*, late orogenic phases formed a greater part of the Caledonian structure. Except for the most southerly part of the Caledonian fold belt, its western edge is masked by the inland ice. In outer coastal regions, where post-Caledonian block-faulting is well developed, much of the area is covered by flat-lying Upper Paleozoic and particularly by Mesozoic sediments. Along the outer coast and also in certain nunatak regions, Tertiary plateau basalts and dyke systems are widespread (cf. Figs. 2 and 3).

South of Scoresby Sund (70° N), the stumps of the Paleozoic fold belt are overlain by a thick pile of Tertiary flood basalts. From this plateau rise the highest mountains of Greenland (up to 3,700 m). The southern arms of Scoresby Sund cut through the basaltic cover into the Caledonian trunk. The fjord valleys are of post-basalt age (Plate I).

In the section of the mountain chain between 70° and 74° N, the Pleistocene ice-erosion has carved particularly deeply. The land between the inland ice and the coast is about 300 km wide, and the ramifications of Scoresby Sund, Kong Oscars Fjord, and Kejser Franz Josephs Fjord separate a mosaic of islands and peninsulas. From the coast to the inland ice the *gipfelflur* climbs from 900 m up to 2,500 m (see Plates II, III) and isolated mountain massifs are approximately 3,000 m high (Fig. 4). The inner fjords are narrow and deep. On their steep, high walls, the geologist experiences a remarkable display of tectonic profiles through the high-grade metamorphic central zone of the Caledonides (Figs. 5 and 6, Plate IV).

From the west, the *inland ice* butts against the mountains and is split into great streams pushing down towards the fjords. The inland ice glaciers flow at a rate of 10–20 metres per day, they calve a vast volume of ice into the fjords (Plates V and VI).

In the summertime, when the fjords are open, the glacier ice sails out to the sea and moves southwards with the pack-ice.

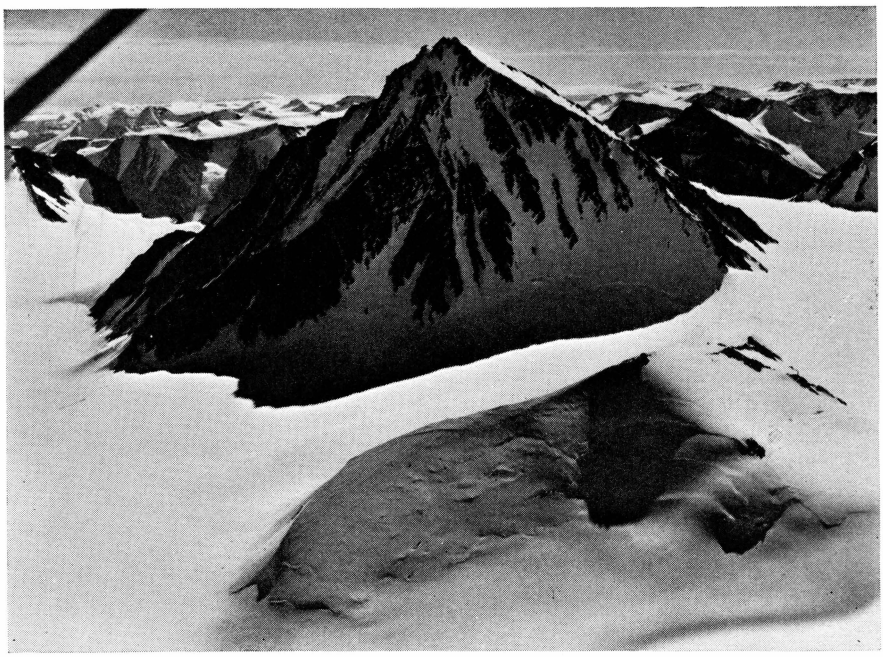


Fig. 4. Petermanns Bjerg, 2,975 m, is the highest mountain in Central East Greenland. This peak and its kindred forming the "Petermann Range" (72°50′–73°30′ N) clearly overtop the average *gipfelflur* of the inner fjord region seen in the background (Goodenoughs Land). — Air-phot. E. HOFER, 1951.

North of the 74th parallel, the inland ice extends far to the east and here the ice-free land is only 100 km wide. This extension of the inland ice is connected with a change in the structure and composition of the underlying rock. In addition, the surface of the Caledonian trunk in the innermost nunatak zone has been protected by Tertiary basaltic lava flows (Fig. 7). At 74° N, the *gipfelflur* is still 2,000 m high; towards the north is changes gradually into a peneplain which at 76° N lies at about 1,500 m.

North of 76° N, the outlines of scenery are on a larger scale, more open but also more monotonous than in the south. Along the coast between 76° and 80° N the plateaus on the peninsulas and islands are lower than 1,000 m. They consist mainly of high-metamorphic crystalline rocks of the central zone of the Caledonian fold belt, which strikes NNE out towards the Greenland Sea. Here, the inland ice pushes wide glacial streams out to sea. Floating glacier tongues and packed ice debris often cover wide inlets. Far to the west of the coast line lie isolated groups of higher mountains; they form nunataks in the inland ice. The biggest nunatak area is Dronning Louise Land (Plate VII); farther north are Tuborgfondets Land (Plate VIII) and Lamberts Land. This chain of

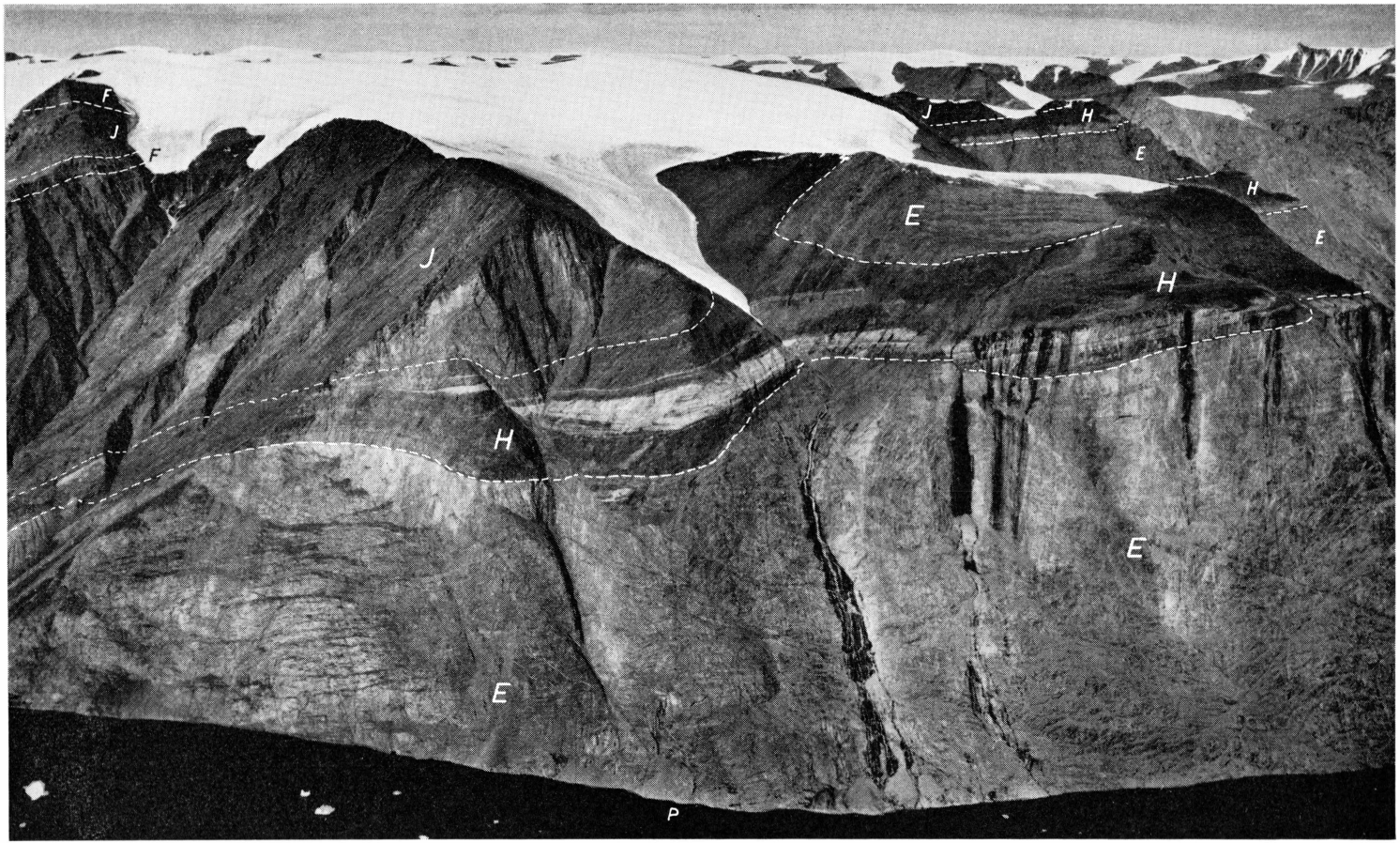


Fig. 5. Ättestupan, a cliff 1,800 m in height, rising vertically from Kejser Franz Josephs Fjord, forms the southwestern flank of the Nigglis Spids dome structure. (For symbols see Pl. XLVI). — Air-phot. E. HOFER, 1951.



Fig. 6. Central part of the "Nigglis Spids migmatite dome" at the mouth of Isfjord. The ice-covered mountain in the middleground left is Nigglis Spids, 2,004 m. (For symbols see Pl. XLVI). — Air-phot. M. Brenneisen, 1949.



Fig. 7. In the inner nunatak region of Central East Greenland, around the 74th parallel, a plateau of Tertiary flood basalts caps the Caledonian trunk at heights of 2,300 m in the west, slightly descending towards the east to some 2,000 m. The photograph shows Tavlen (Hobbs Land) seen from the southeast. There is some indication that these basalt flows continue northwards underneath the inland ice for some 50 km or more. — Phot. H. R. KATZ, 1951.

nunataks marks the *marginal zone of the Caledonian tectogene.* The continuation of the zone is found north of the 80° N in the central mountain chain of Kronprins Christian Land.

Dronning Louise Land is divided into two parts from north to south by the great Caledonian marginal thrust. The eastern half of the nunatak land is built of Caledonian elements; the western half belongs to the intact foreland (Figs. 8 and 9). The mountain groups of West Dronning Louise Land, up to 2,500 m high, are composed of the Precambrian gneiss of the foreland block. On the very innermost of the nunataks, flat lying Precambrian cover beds are also preserved (Fig. 10).

The coastal area between 76° *and* 80° *N* can be divided into the following physiographic members:

— *Dove Bugt* (Fig. 11), cut off from the open sea by the long and narrow Store Koldewey Ø,

— *Germania Land*, which joins the Skærfjorden system in the north, and,

— *Jökelbugten*, the "ice covered bay".

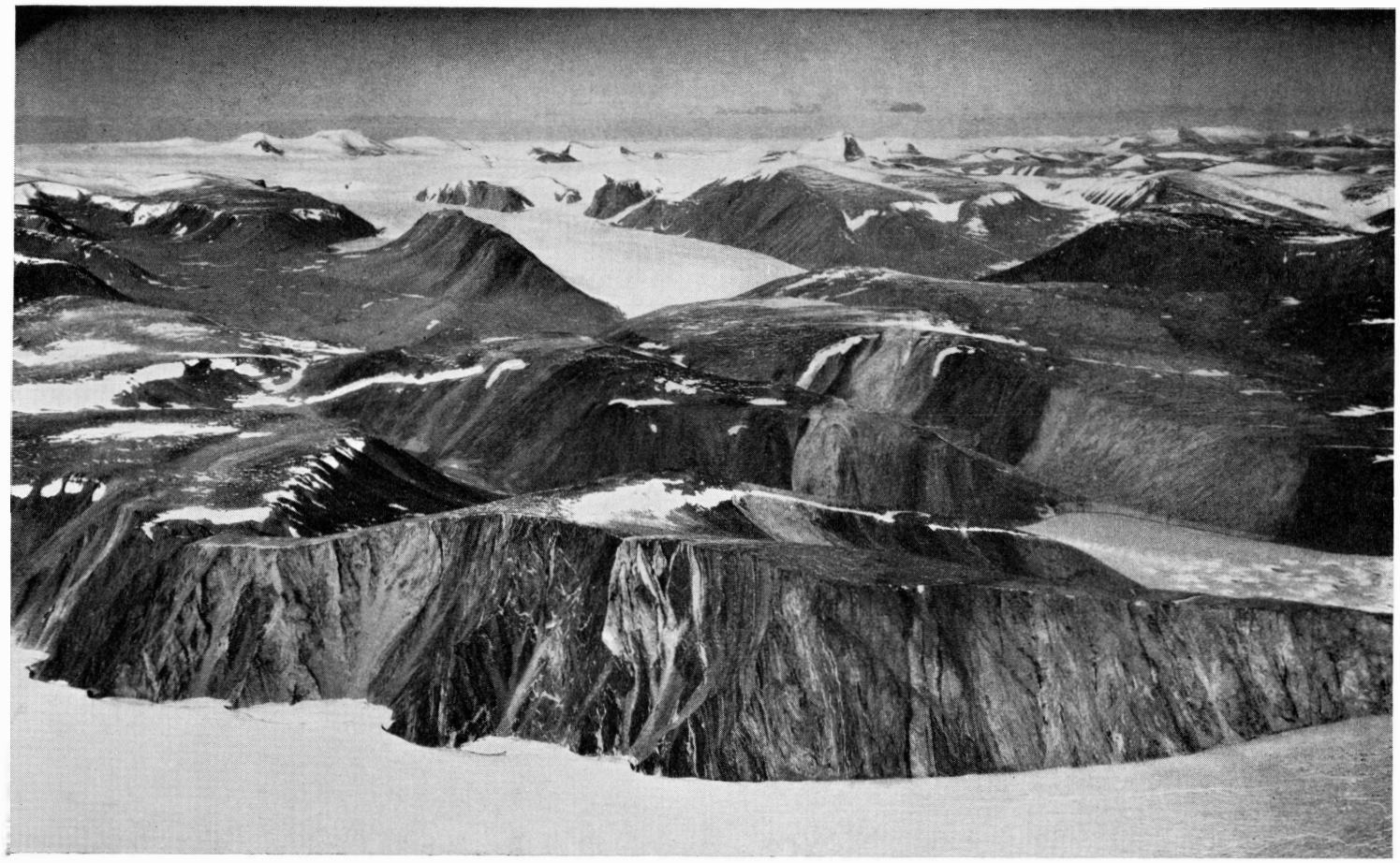


Fig. 8. Aerial view of central Dronning Louise Land with Budolfi Isström in the foreground and Pony Gletscher with Monumentet (M) in the background center (cf. Fig. 9). — Air-phot. W. DIEHL, 1955.

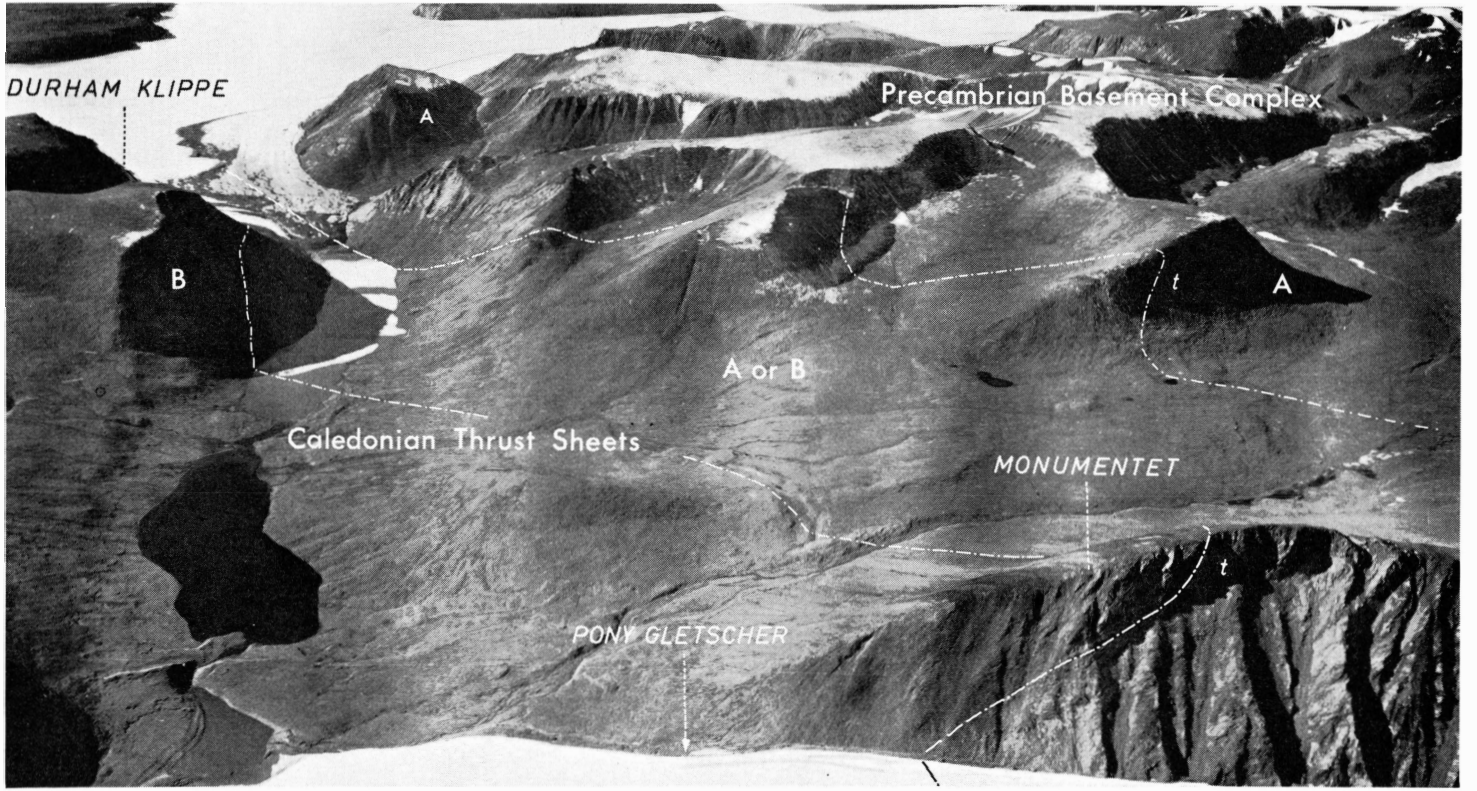


Fig. 9. Marginal thrust belt in central Dronning Louise Land. The Precambrian basement complex to the right, *i. e.* in the west, is part of the intact foreland block. The major overthrust mass exposed in the foreground consists of Carolinidian crystalline series (*B*), which are predominantly metamorphic Thulean rocks. The frontal sheet in between the thrusts (*t*) is likely to represent a parautochthonous slice of basement rocks; however, Groenlandian cover rocks might be partly involved as well.
Geodætisk Institut Eneret Nr. 657 D — SV/12, 337.

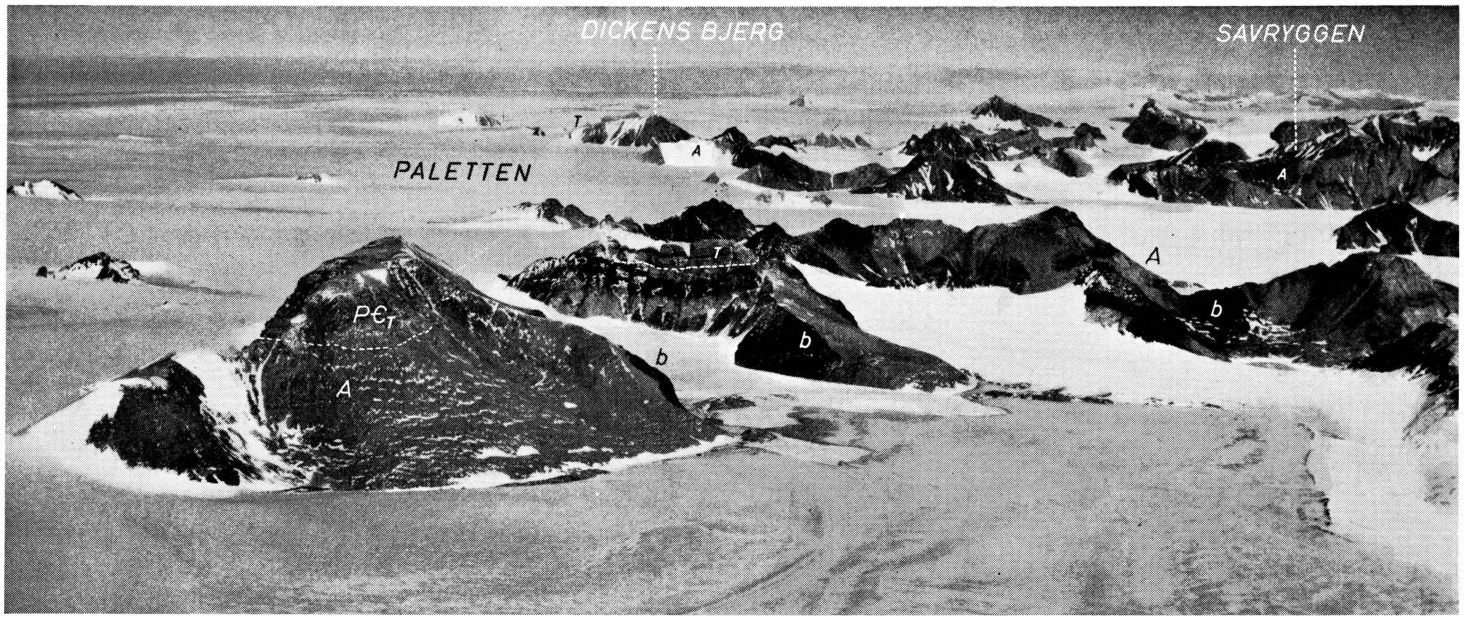


Fig. 10. In southwestern Dronning Louise Land, the foreland block is made up of a deeply truncated Precambrian basement (*A*), which is capped by a flat lying blanket of Thulean sandstones ($P\mathfrak{C}_T$). Basement and cover are cut through by Thulean basalts (*b*). Air-phot. W. Diehl, 1955.



Fig. 11. Aerial view of Dove Bugt (76°30′ N) looking southeast. — Geodætisk Institut Eneret Nr. 656 B-SØ/11,579.

This natural three-part division is brought about mainly by structural conditions. *Germania Land*, for instance, is a far-projecting arm, not only in a geographical sense as it is also an oblique element in the Caledonian structure, built of older crystalline material. It is a more or less intact remnant of the Precambrian Carolinidian fold belt. At this place, the front of Caledonian activation lies relatively far below the present-day outcrop surface. It rises, however, to the north and to the south; both in *Dove Bugt* and in *Skærfjorden* deep-seated Caledonian flow-folding dominates the structural features. (Plates IX and XL).

North of the 78th parallel, the mainland coast again lies far to the west. *Jökelbugten*, covered with permanent ice, is bordered by a line of islands running parallel to the coast (cf. Pl. VIII). *Lambert Land*, the north flank of the bay, stands like a bastion between two broad streams of inland ice. From time to time, the floating ice front joins around the land so that it forms an island in the ice. In fact, Lambert Land belongs to the chain of nunataks, which mark the edge of the Caledonian fold belt.

Kronprins Christian Land forms a tongue of land projecting far towards the northeast. The boundary is marked on the south by the inland ice, and on the west by the Danmark Fjord. To the north lies the Arctic Ocean and to the east, the Greenland Sea, from which two long fjords (Ingolf Fjord, Dijmphna and Hekla Sund) cut across the mountainous coastal area. As in Dronning Louise Land, the Caledonian marginal thrusts cut the region into two parts. In contrast to Dronning Louise Land, however, the eastern half—composed of Caledonian rocks—is rugged and mountainous, whereas the foreland to the west is relatively low-lying and shows a gentler landscape. Here, the foreland consists of a flat-lying series of early-Paleozoic limestones, dipping slightly towards the east (Fig. 12 and 13).

The Caledonian mountains of Kronprins Christian Land have a marked central chain with peaks up to 1,500 m high, the *Prinsesse Caroline-Mathilde Alper* (Plate X) and the *Prinsesse Elisabeth Alper* (Plate XI). These mountains are rugged and carved by glaciers. They consist of Precambrian quartzite, basalt and gneiss, parts of the Carolinidian fold belt which have been stacked together by the Caledonian thrusts, forming a mountain chain of NNE–SSW strike.

The hilly country to the west consists of Precambrian beds which lie as Caledonian nappe units overthrust upon the Paleozoic foreland rocks (Fig. 14).

In the east, post-Caledonian fault lines border the central zone. The sunken block-faulted area along the coast is only a few hundred metres

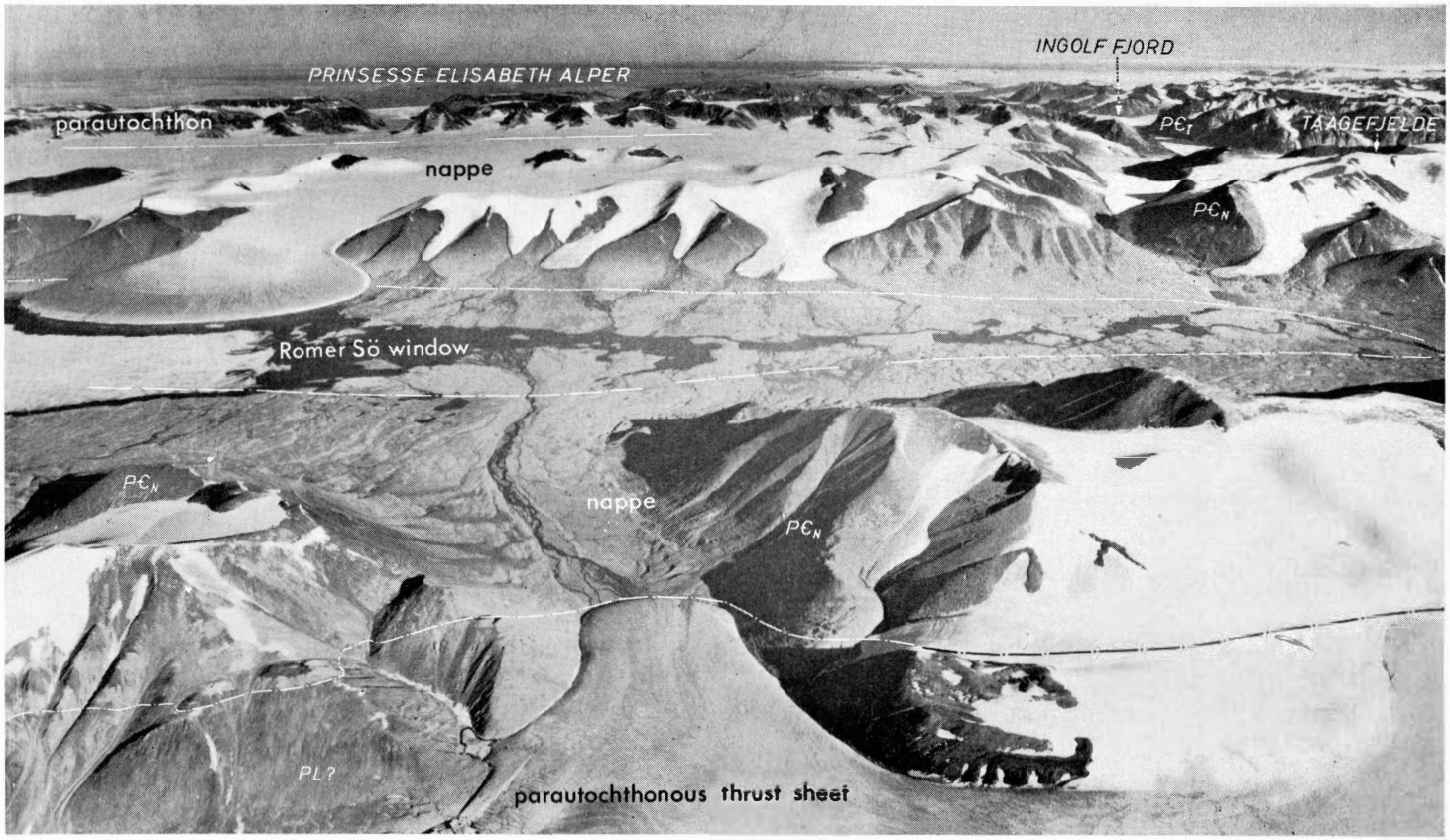


Fig. 12. Central Kronprins Christian Land (81° N), seen from the west-northwest, showing Caledonian nappe and thrust tectonics (cf. Fig. 14 and Pls. X, XI). Geodætisk Institut Eneret Nr. 665 E-SØ/4,992.



Fig. 13. Aerial view of the foreland succession (Mylius-Erichsen Land, ca. 80°50′N/26° W). The pile of Precambrian to Lower Paleozoic beds dips very slightly towards the east. — Geodætisk Institut Eneret Nr. 665 A-NØ/15,162.

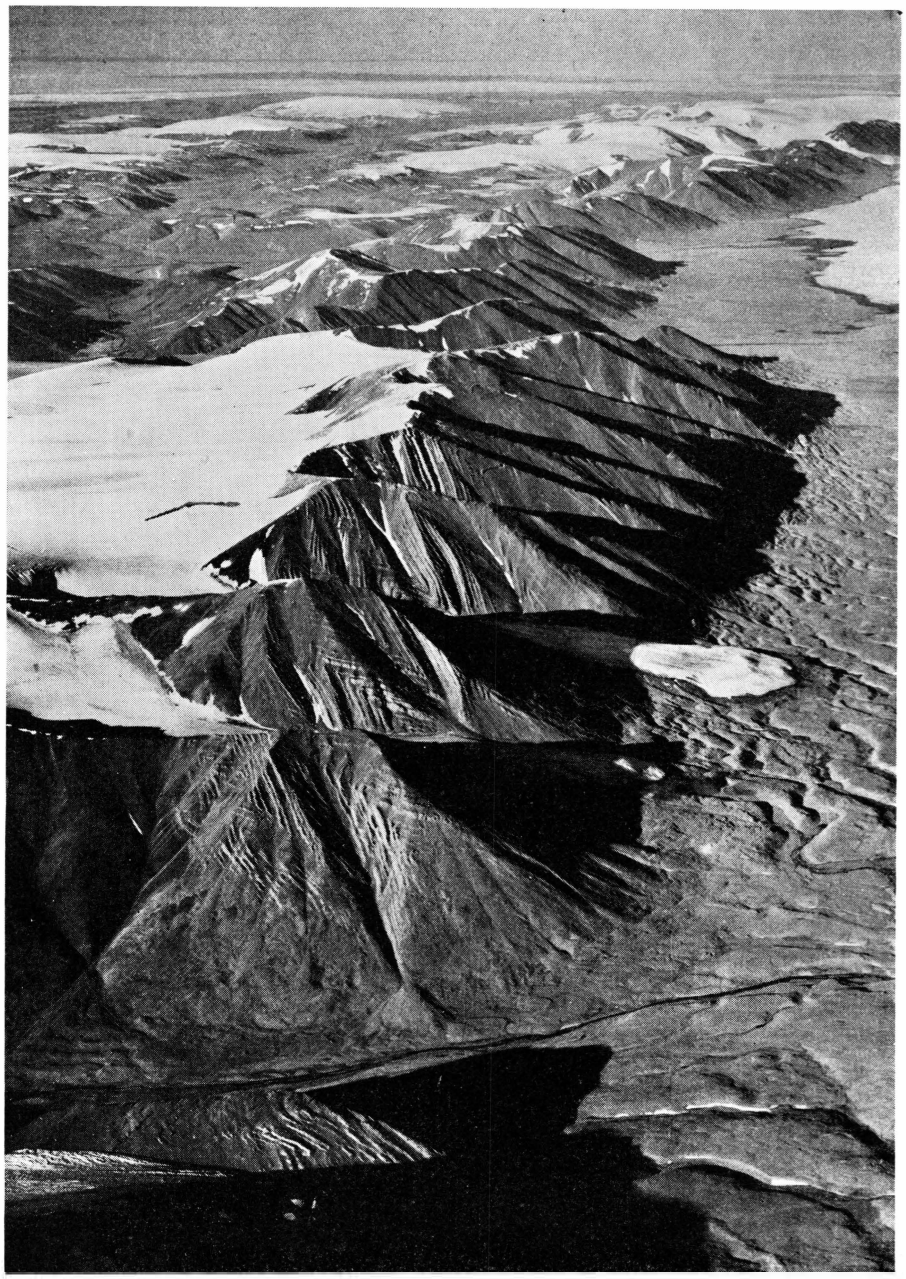


Fig. 14. Aerial view of Vandredalen (80°45′ N) and the hill country west thereof. The uniformly built range in the center involves the frontal portion of the Caledonian nappe sheets. The overthrust mass consists entirely of allochthonous Hagen Fjord strata. The competent members such as the light-colored "Rivieradal Sandstones" are thrown into asymmetrical, tight angular folds. In the background Romer Sø (right) and Prins Frederik Højland (left) are seen. — Geodætisk Institut Eneret, Nr. 665 F-NØ/5,007.

high (Holm Land, Amdrup Land). In these areas, a series of flat-lying late-Paleozoic sediments overlies the Caledonian trunk.

The northernmost part of Kronprins Christian Land carries a cap of highland ice, the *Flade Isblink*. This ice sheet, some 100 km in length, stretches mainly over the low plateau of post-Caledonian cover rocks, which were subjected to very open warping and local thrusting in post-Triassic, presumably Cenozoic times.

OUTLINE OF STRUCTURAL HISTORY

Greenland's geological development can be traced far back into Precambrian times, and the major rock units involved in the Caledonian fold belt of East Greenland developed for the most part during a long period of the Precambrian history. On the basis of radiometric data[36]) available up to the present time, the oldest unit adjacent to the East Greenland fold belt dates back at least to 2.3 b.y. Hence, the pre-Caledonian succession, broken off at some 400 million years ago, is largely controlled by Precambrian events.

It is rather difficult, however, to obtain an accurate reconstruction of these early happenings. Although Greenland consists almost entirely of *Precambrian units*, these rocks are virtually completely hidden by the Pleistocene continental ice. The narrow coastal strips merely display isolated fragments, mostly stumps of deeply truncated ancient mountain systems. These widely separated exposures cannot be related by field-evidence. The difficulty of such a correlation might be illustrated by imagining that the Baltic Shield is today still covered by continental ice and that all one can see of the Fennoscandian Precambrian is a few outcrops along the Norwegian coast, on the Kola Peninsula and in the area of the large Karelian lakes. In Greenland, all further work will thus have to go on lines of isotopic chronology which may yield a basis for grouping these disconnected basement exposures into mineral date provinces.

The pattern of environments recorded in the Precambrian of East Greenland indicates a vast number of events acting from the west as well as from the east. We know less, however, about what was then happening to the east, in the *Scandic region* (*i.e.* the Greenland and Norwegian Seas). It is true that comparisons with Precambrian successions in Spitsbergen, in Scandinavia and in Scotland have been very instructive and stimulating for East Greenland geologists, but they are small help in clearing up the Precambrian development of the crustal segment that is now hidden by the Scandic Sea.

Greenland's Precambrian formations in part show considerable resemblance to those of the rest of the Laurentian block. It seems natural, therefore, that the rock and time terms applied to these formations

[36]) Cf. p. 47.

have been influenced by the North American usage. In some cases, Scandinavian terminology also came into use. At present, a standardization of a world-wide Precambrian nomenclature is difficult to obtain. It is true, however, that the Geological Survey of Canada recently established a definite time-classification of Laurentia's Precambrian. Isotopic age determinations settled a major twofold classification for which the classical terms *Archean* and *Proterozoic* are retained, the dividing line between them being at *2.5 b.y.*, an average date of what is called the Kenoran orogeny. The Canadian authors[37]) are certainly right to apply these terms in their original meaning of time units. Nevertheless, in the course of the past few decades, owing to lack of isotopic dating, the usage of these two terms has become confused by a number of geologists preferring to regard them only as petrogenetic terms, applicable to greater or to less metamorphosed areas of Precambrian rocks.

In Greenland, the Precambrian terminology is still open to discussion. However, with reference to the "Lexique Stratigraphique International" (1956)[38]) and the papers on Greenland in the "Geology of the Arctic" (1961)[39]), the following two terms seem to be widely accepted:

The Precambrian Basement, that is the so-called *Greenland Shield*, is made up of deep-seated rock units of former mountain systems which were worn down into low relief still in Precambrian time. These truncated belts are supposed to be components of the hypothetical continental mass Laurentia, extending from western North America to Greenland. At its northern end, Greenland is indeed nearly connected with the continental block of North America, but farther south, Baffin Bay and Davis Strait separate the comparable shield complexes. The cause of this separation is still awaiting explanation. According to L. Koch (1929 b) and P. B. King (1959), the supposedly permanent continental plate was broken down by faulting, probably initiated in Cretaceous times, but becoming most effective during the Tertiary.

Groenlandian ("Grönlandium", Koch, 1930) is a collective term for all Precambrian sediments of North and East Greenland which cover subhorizontally the peneplaned crystalline basement (*i.e.* the "Greenland Shield"). In North Greenland (Inglefield Land, Peary Land, Mylius-Erichsen Land) and in Central East Greenland, Lower Cambrian beds

[37]) J. A. Lowdon *et al.* (1963). Age Determinations and Geological Studies (Including Isotopic Ages—Report 3), pp. I–IV+1–140, 3 figs., Geol. Surv. Canada, Paper 62–17, (Ottawa).

[38]) J. C. Troelsen (1956). Groenland, Lexique Stratigraphique International, pp. 1–116, 1 fig., Vol. I, Fasc. 1 a, C.N.R.S., (Paris).

[39]) G. O. Raasch, *Editor* (1961). Geology of the Arctic (Proceedings of the First International Symposium on Arctic Geology, Calgary, Alberta, January 11–13, 1960), Vol. I, pp. I–XV+1–732, ill.; Vol. II, pp. 733–1196, ill., (Toronto).

transgress with well-defined contacts across the Groenlandian succession. Hence, the upper limit of the Precambrian strata is definitely established. The lower age limit, however, is unknown and it should be emphasized that the term Groenlandian, if ever used in the sense of a time unit, can be compared only in a general way with the "Proterozoic" in Canada. If the definition of the Groenlandian is somewhat lacking in precision, it is similar in this respect to the definitions of other Precambrian rocks. It should be taken into consideration that the "Shield" which forms the substratum of the Groenlandian beds is not a comparable stratigraphic unit, but a tectono-genetic concept. Therefore, "Groenlandian" is chiefly intended to be used adjectivally.

According to our present knowledge, the *Groenlandian* includes four stratigraphic units, whose age in relation to one another has been only partially established:

In *Northeast Greenland*, two major cycles of Precambrian sedimentation can be distinguished. The older cycle is presented by the **Thule Group**[40]) and the younger by the **Hagen Fjord Group.** These two successions are separated by a period of diastrophism, the **Carolinidian orogeny.**

In *Central East Greenland*, the Groenlandian consists of the **Eleonore Bay Group** and the **Tillite Group.** The two units are separated by a disconformity indicating a distinct change of sedimentary environment in the geosyncline of Central East Greenland.

The Tillite Group varies greatly in both thickness and facies. It is generally agreed that the deposition of this bed group, including two distinct boulder horizons, immediately preceded the Cambrian period, at least in the circum-Scandic domain. In Scandinavia, this striking paleoclimatic event is called the "*Varanger Ice Age*"[41]) and the chronostratigraphic term "Eo-Cambrian"[42]) is applied to the interval of time between the onset of this extensive glaciation and the first appearance of Cambrian fossils (Olenellidae). According to the Scandinavian usage, some authors also introduced this term to the uppermost Precambrian strata (*i.e.* Groenlandian) of East and North Greenland. Apart from the well-defined Tillite Group in Central East Greenland, there is, however, no reliable evidence for assigning this "time" term to further Precambrian strata in Greenland.

[40]) Recent work has rendered it necessary to re-define the term "Thule Formation" established by L. KOCH (1929 b, pp. 220–22).

[41]) O. KULLING (1942, 1951).

[42]) W. C. BRÖGGER (1900). Norges geologi (*in* "Norge i 19de Aarhundred") Bd. 1, pp. 1–32, (Kristiania).

1. PRE-GROENLANDIAN BASEMENT COMPLEXES

Adjacent to the East Greenland Fold Belt

On the east side of Greenland's ice cap, unmodified portions of the Laurentian block are to be found along the coastal strip south of *Kangerdlugssuaq* (68° N). Farther north, basement rocks that have been essentially unaffected by later metamorphic events crop out at only two places on the edge of the inland ice, in *Gaaseland* (70° N) and *Dronning Louise Land* (76°–77° N).

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, or else partly to the Carolinidian, *i.e.* late Precambrian crystalline series. The areal distribution of reworked basement rocks in the fold belt is not shown on the Tectonic Map, which does not differentiate stratigraphic units inside the belt affected by the Caledonian main folding. A tentative statement of the proportions of basement and cover rocks involved in the fold belt has been published earlier (cf. HALLER and KULP, 1962, pp. 20–21).

The basement complex of western **Gaaseland** (70° N) is exposed in a "window", stripped by glacial erosion. To the east it is an actual tectonic window through a Caledonian thrust sheet, which moved from the east. In the western portion, the "window" merely represents a stratigraphic inlier (cf. WENK, 1961b, pls. 12, 13). The basement complex shows a general trend NW–SE and was found to consist of three groups of entirely different crystalline rocks in the following succession: (1) migmatite gneiss group, (2) microcline-augengneiss to microcline-granite[43]), formed by intrusive emplacement, (3) crosscutting amphibolite dikes. The complex was already truncated when the basal beds of the Eleonore Bay Group transgressed across the area, which subsequently became the site of the Central East Greenland geosyncline.

In **Dronning Louise Land** (76–77° N), the basement of the Laurentian block is cut up by steep cliffs so that a considerable relief offers an insight into the structure of the pre-Groenlandian socle. Although these exposures, stretching some 110 km from north to south, would

[43]) *Radiometric dating* was done on a massive variety of biotite-albite-microcline-alkali-granite. The biotite yielded a *K-Ar* age of 1,890 ± 50 m.y., which must be considered as a minimum age since this rock must have been buried for a long time at a considerable depth by pre-Caledonian sediments and been somewhat reheated in Caledonian times. Therefore, due to argon leakage, the true age is certainly older. The *Rb-Sr* ratio of the microcline, providing an age of 2,290 ± 70 m.y., seems to give a much better idea of the general age of this basement complex.

provide excellent ground for study, the remoteness of this nunatak land allowed no detailed research.

In analogy to Scotland, PEACOCK (1956, p. 10) called this basement complex in front of the Caledonian belt, the "Western Gneisses". They were found to consist of (1) an older series of gneiss, probably of sedimentary origin, including basic gneisses and amphibolites, and (2) large granitic intrusions.

The structure of the complex has been traced in rough outline. PEACOCK (*op. cit.* p. 30) noted the general eastern dip of the foliated members, and on my own reconnaissance flights I observed a rather uniform NNE–SSW trend of a few large fold-structures visible (HALLER, 1956c, pl. 11). In southwestern Dronning Louise Land, the fold-axes are almost horizontal; farther north, they plunge gently northwards.

On the Tectonic Map, the internal structure of the pre-Groenlandian basement is not displayed. The general trend of the Dronning Louise Land exposures, however, is shown by an inclined hatching, which was also applied to minor basement outcrops exposed between 78° and 79° N, although the supposed NNE–SSW trend was only ascertained in the western part of Bildsö Nunatakker.

2. PRE-CAROLINIDIAN CYCLE OF SEDIMENTATION: THULE GROUP

The name Carolinidian is derived from the Prinsesse Caroline-Mathilde Alper which forms the backbone of the coastal mountains of Kronprins Christian Land. There, a striking angular unconformity, within the sequence of Precambrian sediments, clearly indicates an intra-Groenlandian diastrophism.

According to LAUGE KOCH's original definition of the "Thule Formation" *sensu stricto*, the sediments of the pre-Carolinidian cycle are united into the **Thule Group.**

The name "*Thule*" is derived from the Danish trading station in Northwest Greenland, and KOCH's definition referred to Precambrian cover rocks and associated minor intrusions ("Thule Formation", L. KOCH, 1916[44]). In the geological literature "Thule" has also been employed in another connection; H. S. WASHINGTON[45]) designated the Tertiary basalts around the North Atlantic and the Scandic as "Thulean

[44]) Cf. L. KOCH (1929 b, pp. 16–18).

[45]) H. S. WASHINGTON (1922). Deccan traps and other plateau basalts, pp. 765–803, 2 figs., Bull. Geol. Soc. Am. **33** (New York).

Basalts". This has given rise to an ambiguity in the use of the name "Thule". As Precambrian basalt intrusions occur in abundance embedded in the sediments of the Thule Group in the area around Station Thule (Northwest Greenland), WASHINGTON's designation may easily give rise to misunderstandings. The term "Thulean Basalts" for the Tertiary plateau basalts should therefore be rejected, especially since the name "Brito-Arctic Province" provides a convenient term for the young eruptives. Hence, whenever "**Thulean intrusives**" are mentioned in publications by members of the Danish East Greenland Expeditions, they always **refer to Precambrian** eruptive rocks.

Stratigraphy and sedimentary environments.

Sediments referred to the Thule Group cover a wide area of North Greenland. Along the east and west coasts of Greenland, Thulean beds are traceable southwards as far as the 76th parallel. In East Greenland, these outcrops can be divided basically into regions of autochthonous and regions of allochthonous rocks. Undoubted autochthonous sedimentary successions are found on the foreland block of the Caledonian belt, (cf. Fig. 3), that is in western *Dronning Louise Land* and in the area *Danmark Fjord–Independence Fjord.*

In the coastal area between 76° and 81° N, sediments—in part metamorphic—referred to the Thule Group lie within allochthonous blocks which were thrust westward during the Caledonian movements. The distance of transport is unknown but seems to be greater in the south than in the north.

On the Tectonic Map, transgression planes of pre-Caledonian age are shown only in the foreland area, including parautochthonous massifs in the central chain of Kronprins Christian Land, as well as parautochthonous sheets in the marginal thrust belt, stretching from Lambert Land (79°30′ N) over Tuborgfondets Land and Bildsö Nunatakker to the southern tip of Dronning Louise Land (76° N). The Thule Group, in turn, is bounded both above and below by well defined marker planes, the lower one being the surface of the basement block. The upper boundary of the succession is the surface of the post-Carolinidian peneplanation, which is a distinct datum plane of intra-Groenlandian age. This boundary, on the Tectonic Map indicated as "base of post-Carolinidian strata", is clearly recognizable in the whole of Northeast Greenland. At many places, the younger Precambrian strata overlie folded Thulean beds with remarkable angular unconformity (Fig. 15).

Within the Thule Group there are unfortunately no marker beds which can be regarded as time horizons with any certainty. The succession, thus, can only be subdivided on the basis of *lithofacies.* Hence,

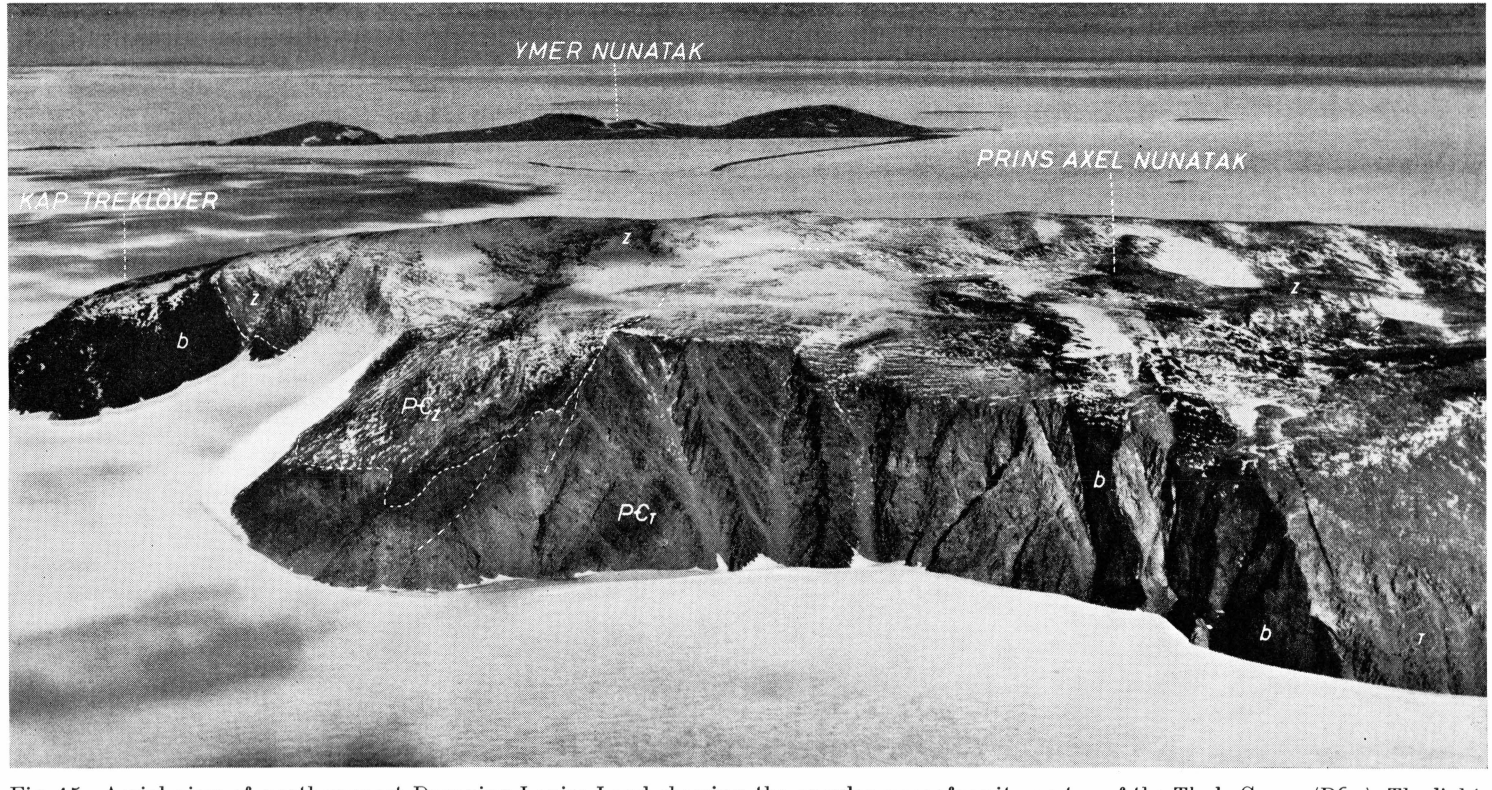


Fig. 15. Aerial view of northernmost Dronning Louise Land showing the angular unconformity on top of the Thule Group ($P\epsilon_T$). The light-colored Thulean sandstones are invaded by large basic dikes (b). The cover strata, called the "Zebra Series" ($P\epsilon_Z$), are referred to the post-Carolinidian Hagen Fjord Group. The crumpling about NNE axes evident in the cover strata is due to Caledonian movements. — Phot. W. DIEHL, 1955.



Fig. 16. South wall of Mørkefjord (77° N) showing base of Lower Thule Group, consisting of light-colored marble-quartzite beds associated with amphibolites. The highly metamorphic succession forms a recumbent, complex refolded syncline, under and overlain by reworked basement (to the right). Refolding is due to Caledonian superimposition on Carolinidian structures. Air-phot. W. Diehl, 1955.

we recognize sedimentary units whose basis of definition is dominantly lithological. In the area concerned, there are three units:

(3) Psammitic strata (red bed facies as well as non-red sandy facies) of dominantly non-marine character. This unit, up to 3,000 m thick, is distributed across the whole area of outcrops of the Thule Group. In the north and east it was found to overlie the marine succession (2); in the western part of Dronning Louise Land, it transgresses directly across the basement.

(2) Semi-pelitic succession, some 3,000 m thick, of acyclical beds which accumulated in a geosynclinal trough. (Greenschists may be present in this succession as well).

(1) Quartzite-limestone beds, some 200 m thick, forming the basal part of the sequence (2).

Where all three lithological units are found together, they overlie each other in the above order (3 highest, 1 lowest). Therefore, tentatively, unit (3) is called the *Upper Thule Group* (continental to epicontinental), and units (1) and (2) the *Lower Thule Group* (marine).

The rocks of the Lower Thule Group are confined almost completely to areas now involved in the Caledonian thrust-fold belt. Although these geosynclinal accumulations are widespread in the coastal mountains of Northeast Greenland, we know little about their lithology since field-investigations have been carried out only in a few localities. Moreover, most of these beds have been affected by both Carolinidian and Caledonian events (Fig. 16).

The psammitic *Upper Thule Group* has a far greater areal distribution than the underlying semi-pelitic units, and represents a change of environment. This change in depositional conditions was probably due to an increase in the relief energy of the source area. In the area to the west, such as in western Dronning Louise Land, the Thulean psammites including coarse clastics at base are dominantly *red beds* of a fluvial-eolian-littoral environment. They accumulated on a continental platform from which pre-existing cover rocks (presumably equivalents of the Lower Thule Group) were then removed and redeposited. To the east, in the coast range between Prinsesse Elisabeth Alper and Bildsö Nunatakker, the psammitic strata which accumulated on top of the geosynclinal sequence are considerably thicker than those in the west. Here, the psammites show yellowish, grey and greenish colors and are supposed to have been laid down in a neritic environment. There is some alteration of light-colored psammitic and dark semi-pelitic bands at the base of this upper complex.

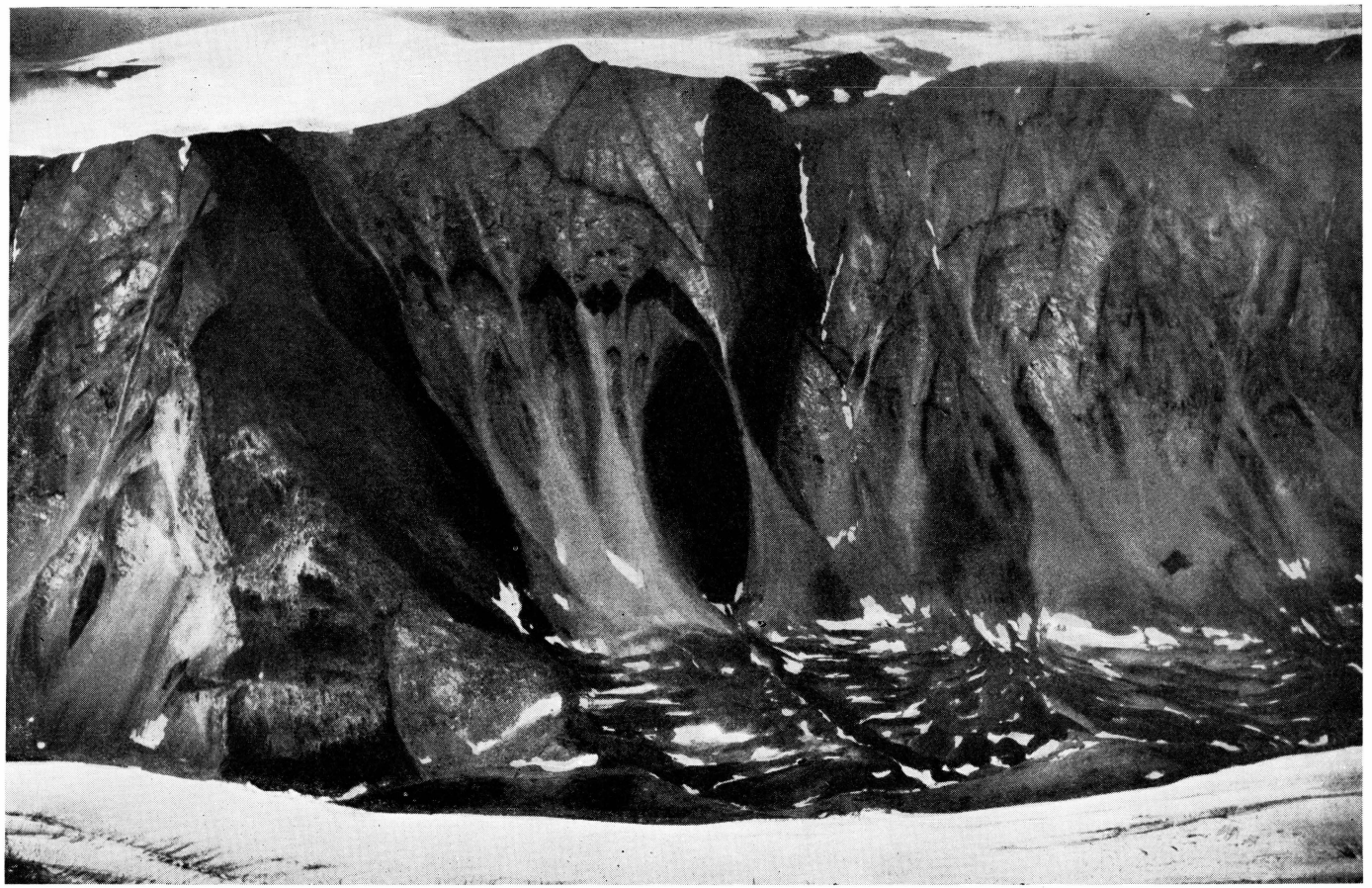


Fig. 17. Post-Carolinidian generation of Thulean basalts forming extensive, almost vertical feeding channels. South cliff of Hovgaard Ø. — Air-phot. W. DIEHL, 1958.

Minor intrusions in the Thule Group.

Ubiquitous occurrence of basaltic dikes and sills (Thulean basalts) is a striking feature of the Thule Group. Both in Northwest Greenland (Thule District, Inglefield Land) and in the whole of Northeast Greenland, all sorts of Thulean strata are intensely penetrated by intrusives, yielding a stereotype appearance over a distance of more than 1,300 kilometers. The Thulean igneous activity was certainly a phenomenon of continental-wide scale.

In Northeast Greenland, there is evidence of at least two periods of basaltic irruption. The first occurred after the completion of Thulean sedimentation. Thus, this generation became subsequently involved in the Carolinidian tectonics. The final stage of this mountain building is characterized by faulting in relation to which a second generation of basaltic dikes was emplaced. These post-folding intrusions frequently form bulky vertical sheets up to several hundred meters wide (Fig. 17). It is possible that these channels fed an extensive area of Precambrian plateau basalts. In the section affected by Carolinidian movements, the younger dikes clearly cut across distorted and partly metamorphosed older ones (Plate XII).

The Thulean magmatic activity also produced minor occurrences of red porphyries. The age relation of this acid rock group to the whole magmatic cycle is not definite, but it is highly probably that it represents the ultimate event.

3. THE CAROLINIDIAN OROGENY

The Carolinidian fold belt settled mainly along the geosynclinal basin where the Lower Thule Group accumulated. It is traceable from Independence Fjord (82° N) to Dove Bugt (76° N), that is over a distance of some 800 km. South of Dove Bugt, the belt strikes southeast towards the Greenland Sea. In North Greenland, the fold pattern disappears underneath a cover of late Precambrian and Paleozoic strata (Franklinian Geosyncline). A westerly extension of the Precambrian chain probably emerges at the north coast of Ellesmere Island (Fig. 18).

In most places, however, this Precambrian structural pattern is distorted and broken so that we are not able to restore completely its arrangement and its style of deformation. The Carolinidian pattern was severely affected by the thrusting, refolding, and metamorphic action of the Caledonian main orogeny. Thus, considerable portions of the Carolinidian trunk—then buried under a load of younger cover rocks—were broken down and forced into new positions by large-scale thrusting

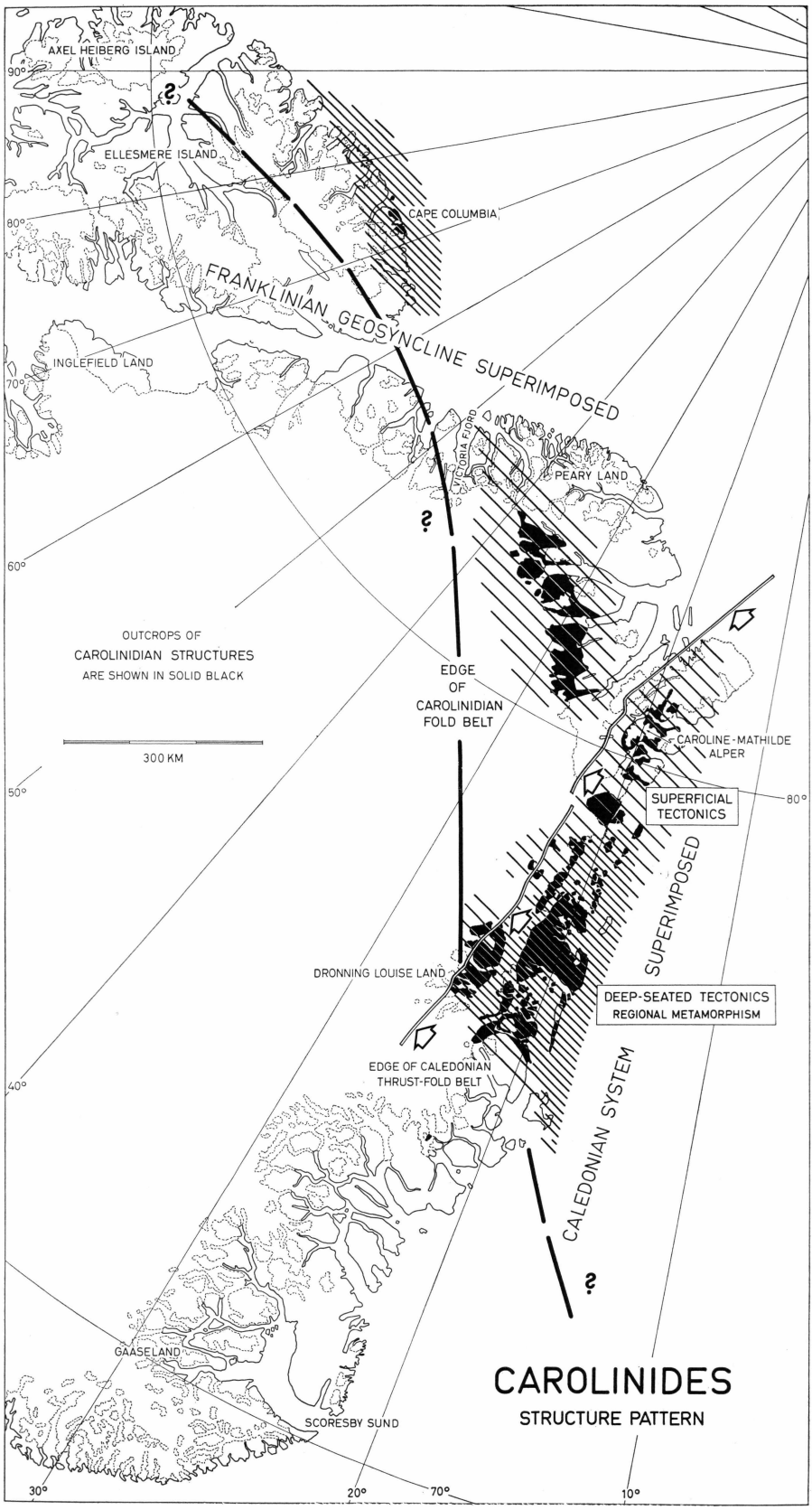

AXEL HEIBERG ISLAND
90°
ELLESMERE ISLAND
80°
CAPE COLUMBIA
FRANKLINIAN GEOSYNCLINE SUPERIMPOSED
INGLEFIELD LAND
70°
VICTORIA FJORD
PEARY LAND
60°
OUTCROPS OF
CAROLINIDIAN STRUCTURES
ARE SHOWN IN SOLID BLACK
300 KM
EDGE
OF
CAROLINIDIAN
FOLD BELT
CAROLINE-MATHILDE
ALPER
50°
80°
SUPERFICIAL
TECTONICS
SUPERIMPOSED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

Fig. 18.

towards the west. In most places the total amount of this displacement is unknown, but it is evident that the Caledonian pattern causes quite different parts of the truncated Carolinidian chain to lie beside and over each other.

In order to reconstruct the Carolinidian mountain system, we have to distinguish in principle:

(a) *Carolinidian segments which were not affected by Caledonian movements* and which are still today at the place of their Precambrian origin. This refers to the pattern revealed in northwestern Dronning Louise Land. There, the Thulean beds and associated intrusions are unconformably overlain by psammitic strata referred to the Hagen Fjord Group. In the south, in the catchment area of Budolfi Isstrøm, the younger Precambrian succession lies conformably on the sub-horizontal Thulean sandstones. There is a hiatus but no pronounced break between the two sedimentary groups. This area was not affected by Carolinidian movements and thus represents part of the Precambrian foreland. In northwestern Dronning Louise Land, north of Admiralty Gletscher, the succession transgresses across folded Thulean beds (cf. Fig. 15) and comes to lie in places directly on the basement gneisses, from which the Thulean beds were stripped by the post-Carolinidian erosion. In this area we enter the Carolinidian fold belt. Although the cover beds and folded pavement were subjected to weak Caledonian folding, the restored plane of transgression clearly indicates a Carolinidian pattern of open fold-structures trending approximately NW–SE. The intensity of folding increases distinctly towards the northeast where the angular unconformity is considerable.

Far to the north, in the environs of the head of Independence Fjord (not shown on the Tectonic Map) another autochthonous pattern of very open Carolinidian folds is preserved. There, the axes trend E–W to ENE–WSW, the crests lying 20 to 25 km apart.

(b) *Allochthonous Carolinidian segments*, in the form of substantial parts of Caledonian thrust-blocks and nappes, are to be found throughout the marginal belt of the Caledonides, that is, from Dronning Louise Land to Kronprins Christian Land. In the south there are mainly Carolinidian complexes of gneiss, in the north, of slightly to non-metamorphic sediments. These structural remnants were thus derived from different tectonic levels in the Carolinidian mountain belt. On the Tectonic Map, the structural symbols were accordingly differentiated by showing the fold-axes of the infrastructure with thinner red lines than those of the superstructure. The predominant trend of the folds within these westward thrust relics of the Carolinides is NE–SW to N–S, but in detail the axes diverge and form a complex pattern.

The eastern part of Dronning Louise Land is made up of a large thrust sheet, the displacement of which can only be estimated (probably 50 km or more). It represents a fairly continuous complex of deep-seated Carolinidian structures. Part of the complex is derived from the pre-Groenlandian basement, the greater portion, however, consists of metamorphic schistose strata which can be related to the Lower Thule Group (Lithofacies 1 and 2).

In the nunataks of Tuborgfondets Land, superficial NNW–SSE folds of several kilometers width represent the remnant pattern. To the east, along the coast, we enter higher units of the Caledonian thrust pile. There, plastically folded Carolinidian gneisses, including metabasites, were coaxially overprinted by the Caledonian pattern so that the general trend of both structure systems is now NNE–SSW.

In Lambert Land, open folds of the Carolinidian superstructure curve from NNW–SSE in the south to a NE–SW trend in the north. This curving of the axes is a secondary effect due to Caledonian thrust tectonics.

In the coast range of Kronprins Christian Land, the ancient fold pattern, restored from outcrops of slightly or non-metamorphic Thulean psammites, shows a general strike of NE–SW to ENE–WSW. The fold-axes diverge and their directions are entirely independent from the Caledonian adjustment. In contrast to the brittle mode of Caledonian deformation (mainly easterly dipping thrusts), a few Carolinidian complexes show plastic flow folding of infrastructural aspect. For instance, continuous cliff sections of Dijmphna Sund (Plate XIII) and inner Ingolf Fjord (Fig. 19) display metamorphic to gneissified beds, intimately folded together with numerous basic dike intrusions. The trend of these folds differs from place to place. The distribution of Carolinidian metamorphic complexes is scattered throughout the Caledonian pattern; their intra-Groenlandian age is also indicated by a post-folding generation of basic dikes which are truncated at the base of the Hagen Fjord Group.

(c) A great number of *isolated fragments of the Carolinidian gneisses* are also *involved in the migmatitic central zone of the Caledonides.* On the islands and peninsulas of Dove Bugt, elongated masses of Carolinidian gneisses occur as deformed relics. They were caught up in the deeper level of the Caledonian main orogeny, yielding a mosaic of resistant blocks with swarms of NW–SE folds.

In Germania Land, the Carolinidian crystalline rocks have remained more or less intact, forming a continuous complex of NNW trend. In southern and northern Germania Land, all transitions exist between the untouched and the completely recrystallized old gneisses.

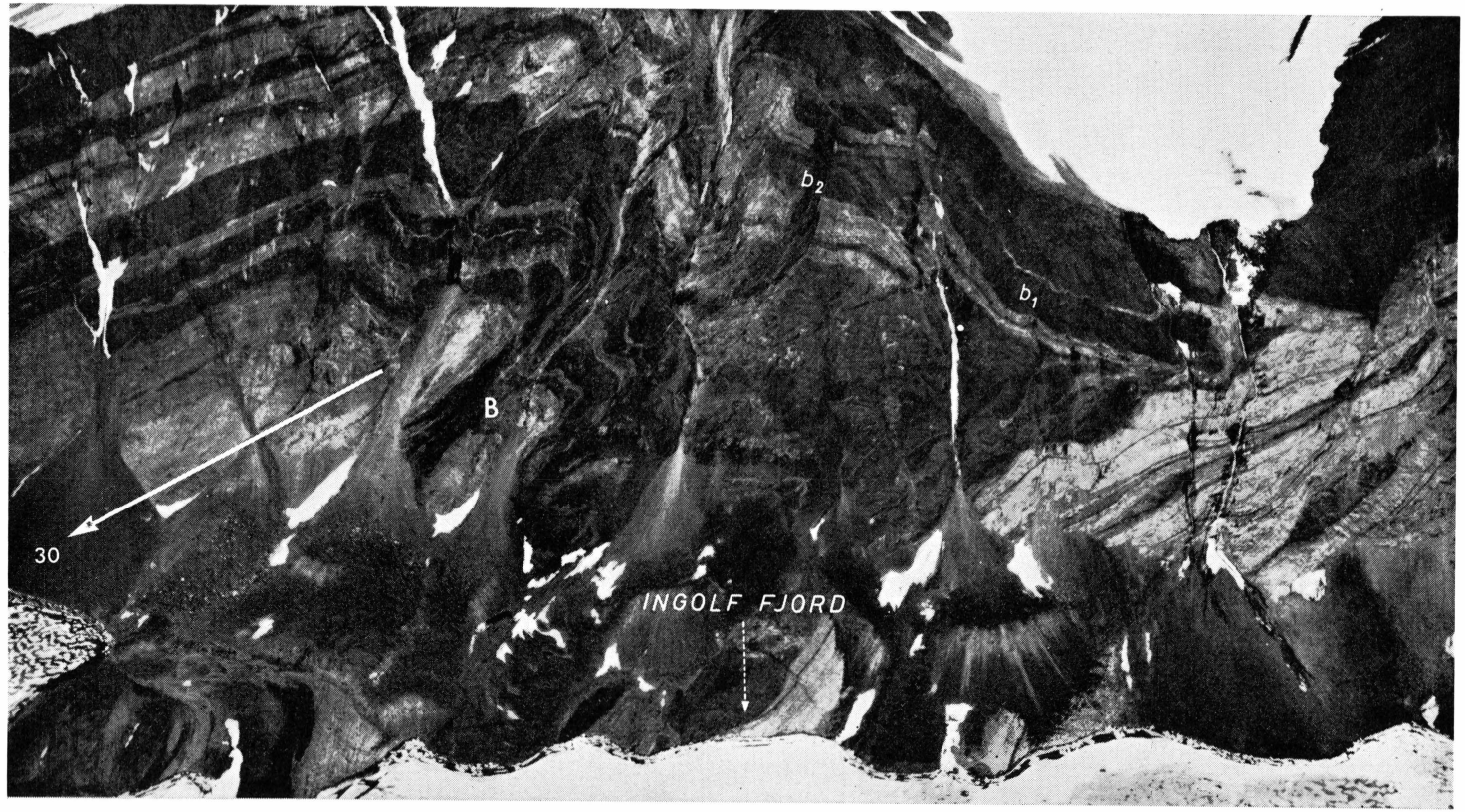


Fig. 19. Carolinidian metamorphic complex (B) at the south coast of inner Ingolf Fjord (80°38′ N). The major fold exposed plunges east-northeasterly. There are light-colored gneissified psammites intimately folded together with early basic sheets (b_1), but cut through by younger basalts (b_2). — Air-phot. W. DIEHL, 1958.



Fig. 20. Gneissified Thule Group involved in the Caledonian infrastructure zone of eastern Lambert Land. Coast cliff northeast of Kap Zachariae (79°05′ N). — Air-phot. W. DIEHL, 1958.



Fig. 21. Laccolithic basic intrusion in gneissified psammites, presumably of Thulean age. Trækpasset, southern part of Store Koldewey Ø (76°10′ N). — Air-phot. W. DIEHL, 1955.

A large part of this Carolinidian crystalline material evidently represents reworked pre-Groenlandian basement, but thick successions of metamorphosed Thulean sediments are also found as part of this Carolinidian remnants. In all these units, metabasites are ubiquitous (Figs. 20 and 21).

Like the complex of eastern Dronning Louise Land, the remnants spread over Dove Bugt and Germania Land represent deep-seated tectonic levels in the Carolinidian mountain structure. From the present arrangement of the Carolinidian segments, we may conclude, indeed, that most intense folding and metamorphism affected the section between 76° and 78° N. But we have also to consider that the syngenetic spatial position of these segments must be placed farther east and that the Carolinidian block was not only sliced and pushed westward in the

form of brittle sheets, but also shifted to a higher crustal level by Caledonian transport. However, north of the 78th parallel, the front of Carolinidian metamorphism descends so that in Tuborgfondets Land and Lambert Land the Thulean beds suffered remarkably lower metamorphism. There, the basal unconformity between cover and pre-Groenlandian basement is not seriously obscured by metamorphic action. In the coastal mountains of Kronprins Christian Land, gneissified Thulean beds are restricted to parts of large-scale culminations in the Caledonian structure. But on the whole, in this northern area, the Thulean beds are only slightly altered and in parts entirely unmetamorphosed. This is also the case with the extensive Thulean exposures to the west of Danmark Fjord.

About the postulated continuation of the Carolinidian belt towards east and south, nothing is known for certain. Presumably, the fold zone stretched out into the Greenland Sea south of the 76th parallel and there played an essential part as a marginal element in the development of the Central East Greenland geosyncline.

4. POST-CAROLINIDIAN CYCLES OF SEDIMENTATION

When the Carolinidian belt had ceased folding, block faulting disarranged the mountain structure and the second generation of Thulean magma rose, mainly along these fractures. Detritus derived from the fold belt and its associated basalts occurs in the basal sequence and lower strata of the Precambrian Hagen Fjord Group. This succession is traceable from southern Peary Land over Hagen Fjord to Kronprins Christian Land. However, lithofacies and thickness variations indicate that, in the progress of denudation, the Carolinidian chain acted as a long-enduring positive area which had an essential influence upon the depositional environments in Northeast Greenland. The Carolinidian trunk stood as a NNW–SSE barrier dividing the sedimentary area into northern and southern regions which developed in entirely different ways (Fig. 22).

A. Basin-and-Swell Region of Northeast Greenland

The Precambrian succession which accumulated to the north of the barrier is called collectively the **Hagen Fjord Group** (Groenlandian); its depositional area can be divided into two tracts of different character: (a) the intracratonic *Hagen Fjord Basin*, and (b) *the marginal trough*

east of Kronprins Christian Land. The two negative elements were separated by the so-called "Sæfaxi Ridge" (Kronprins Christian Land) which acted as a horst structure subsequent to the Carolinidian event.

A restored section of the sedimentary filling of these depositional tracts, showing the plane of Lower Cambrian transgression as time datum level, has been published by HALLER and KULP (1962, p. 37).

Hagen Fjord Basin.

On the tableland between South Peary Land and Kronprins Christian Land, these late Precambrian beds overlie the truncated Thule succession. At Hagen Fjord, the pile approaches 2,000 m in thickness; in southern Peary Land the thickness is 700 m, and in Kronprins Christian Land only 400 m. There was thus a *shallow basin* developing between the truncated Carolinidian mountain belt (exposed in Kronprins Christian Land) and the old stable block. Its present extent is at least 350 km, and arms of the basin may have continued far to the west and southwards as far as Dronning Louise Land ("Zebra Series").

The well-stratified sequence which accumulated in this intra-cratonic basin was derived mainly from the stumps of the Carolinidian mountain chain. At its base coarse clastic beds were found to transgress across a hilly Precambrian land surface. In part, the basal strata are of tilloid aspect. This is followed by a sandstone sequence interbedded with thin mudstones. Limestone and dolomite appear near the top of the pile. Locally, the dolomites contain *Collenia* and very large *Cryptozoan? reefs.*

The flat-lying Hagen Fjord succession is truncated by an irregular erosional surface over which then the Lower Paleozoic transgressed (see p. 64).

Marginal Trough.

To the east of the stumps of the Carolinidian chain, an extracratonic belt of thick sediments was deposited. Its lithological association and also its high rate of deposition indicate a geosynclinal tract with cratonal land on the west side. This pile of late Precambrian sediments approached 5,000 m in thickness. It was brought into Kronprins Christian Land by Caledonian movements. Lower Paleozoic beds have not hitherto been ascertained within this allochthone.

The Caledonian structure pattern of the coastal mountains of Kronprins Christian Land is not known in detail and it is still open to question where the "root zone" of the sedimentary nappe assemblage was located. FRÄNKL (1954, pp. 66–70, pl. 1) assumed that the morphological depression Hekla Sund–Spærregletscher was the root and hence he called the original depositional area the "Hekla Sund Basin". From my investigations in 1958, I found this zone to consist mainly of semi-pelites of the

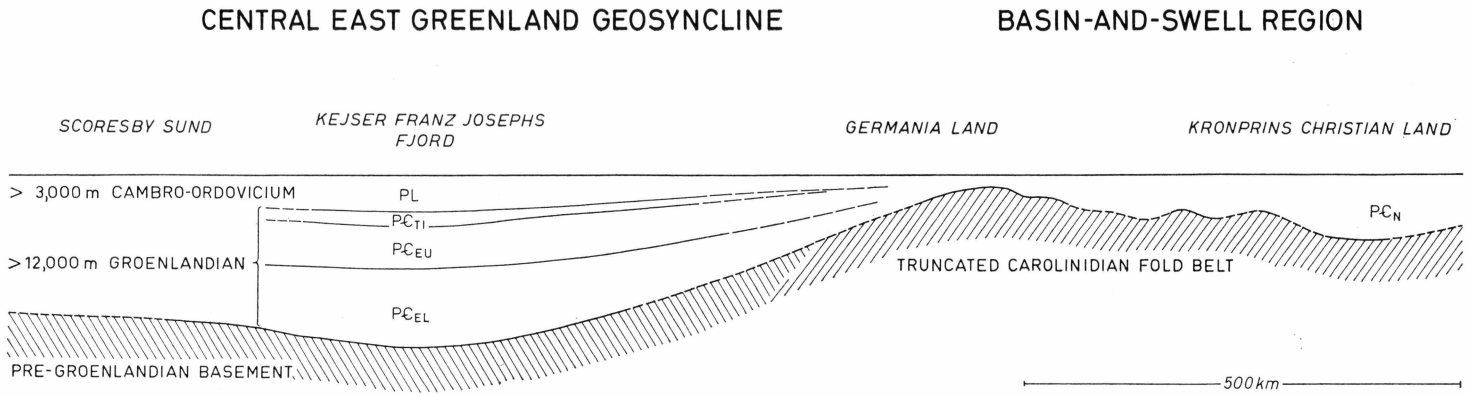


Fig. 22. Diagrammatic section following the orogenic axis of the East Greenland Caledonides. The graph shows the vertical distribution of basement rocks and post-Carolinidian cover at the beginning of the Paleozoic mountain building.

The *Central East Greenland* geosyncline includes four cycles of sedimentation: Lower Eleonore Bay Group ($P\epsilon_{EL}$), Upper Eleonore Bay Group ($P\epsilon_{EU}$), Tillite Group ($P\epsilon_{TI}$), and Cambro-Ordovician (PL). In Northeast Greenland, the pile of Hagen Fjord Group beds accumulated in the 'marginal trough' ($P\epsilon_{N}$) is likely to correspond to the Upper Eleonore Bay Group. It is assumed that here some 2,000 m of Cambro-Silurian beds followed the Groenlandian (see p. 65).

Lower Thule Group. Thus, the original position of the geosynclinal prism was presumably somewhere to the east of the present coast area.

The following stratigraphy of Hagen Fjord beds, originally deposited in this marginal trough, was constructed from the overthrust pile in central Kronprins Christian Land: The *lower strata* (2,500 m) consist of mudstones and greywackes, rapidly accumulated. The *middle strata* (2,000 m) show alternation of sandstone and dark mudstones. The *top part* of the pile consists of carbonate rocks (400 m) which are to be related to the dolomite succession on top of the Hagen Fjord Basin. These beds, which include numerous cryptozoan reefs, indicate a uniform neritic environment for the whole of this northern region.

Environments during Lower Paleozoic sedimentation.

In summing up the deposition of the Cambro-Silurian in Northeast Greenland, it seems convenient to recapitulate the previous Groenlandian environments. Fig. 23 is a diagrammatic section across Northeast Greenland, showing cumulative subsidence through Groenlandian and Lower Paleozoic times. From this it is evident that the keel of the sinking basins shifted considerably in the course of time.

During the change from Precambrian to Paleozoic times, a new cycle of sedimentation was initiated. Throughout the entire area emergence preceded the transgression of the Cambrian sea. At most places there exists an erosional contact or even a slight angular unconformity indicating epirogenetic movements. Linked with these movements, the stumps of the Carolinidian belt again came into play to act as a barrier and to control the lithological association of the Cambrian formations. Red sandstones[46]), which in turn are disconformably overlain by fossiliferous Lower Cambrian dolomites[47]), mark the striking change from Precambrian to Paleozoic sedimentation. These strata show remarkable stratigraphic thinning towards the reviving barrier. This is also true for a bulky succession of Ordovician-Silurian limestones[48]). In the area of Centrumsø, the formation is some 2,500 m thick, and from the window exposures in Sæfaxi Dal, FRÄNKL (1955a, p. 22) reported a thickness gradually thinning from 800 m at Enhjörningen to 300 m at Hekla Sund. This is held to be largely a result of the depositional environment since no evidence for important tectonic thinning was found.

We do not know how far to the west the Lower Paleozoic sea encroached, but it does not seem probable that a thick pile of this Ordovician-Silurian limestone continued far into Mylius-Erichsen Land. It is agreed that the Paleozoic formations generally wedged out towards

[46]) "*Kap Holbæk Sandstone*" (presumably Lower Cambrian).
[47]) "*Danmark Fjord Dolomite*" (Lower Cambrian).
[48]) "*Centrum Limestone*".

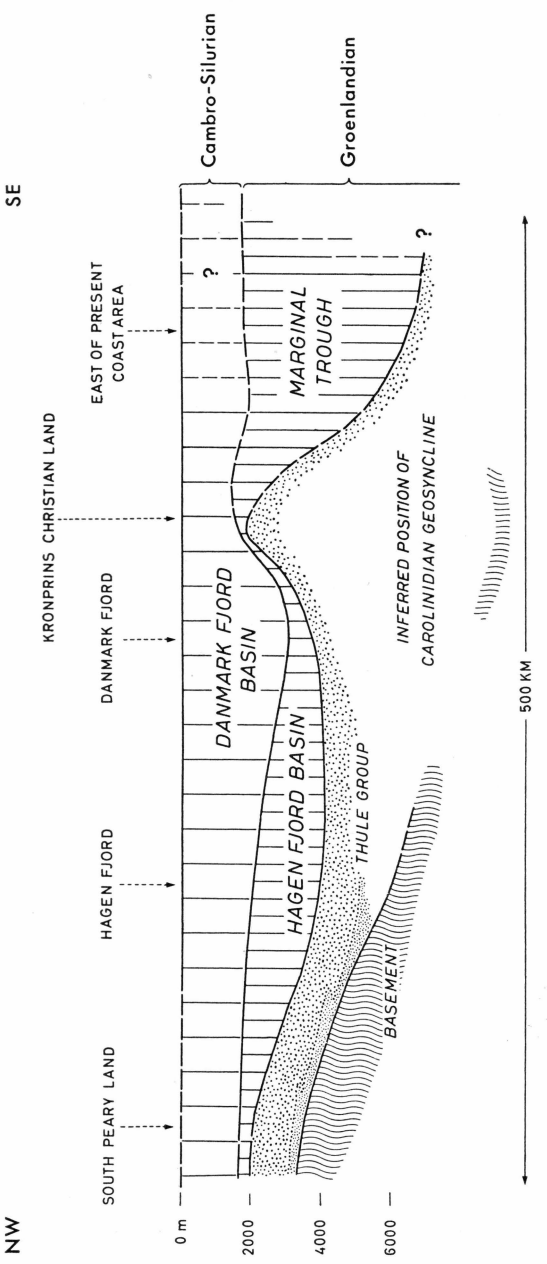


Fig. 23. Diagrammatic section showing cumulative subsidence through pre-Caledonian times in Northeast Greenland. Note the repeated shift of basin axes.

the west. Therefore, it has been concluded that the maximum subsidence through Lower Paleozoic times occurred around Danmark Fjord. The axis of the intracratonic basin, which was initiated in late Precambrian times, evidently shifted from Hagen Fjord eastwards to Danmark Fjord. The Lower Paleozoic area of sedimentation is thus called the **Danmark Fjord Basin.** It should be noted that the Ordovician and Silurian faunas of Northeast Greenland have a high proportion of forms common to Northwest Greenland, indicating free faunal intercommunication.

In Northeast Greenland, at the close of Silurian times, a complex succession of sedimentary events came to an end. The unstable area became then the site of the Caledonian mountain-building and consequently part of Greenland's present-day continental mass.

B. Geosyncline of Central East Greenland

In Central East Greenland, south of the Carolinidian chain a geosyncline condition was established over an extensive area, a subcircular basin sinking intermittently. Initially, the longer axis of the subsiding basin may have been directed north-easterly but in the later stages it lay mainly north-south. The strata laid down in the geosyncline reached a thickness of about 16,000 m, the bulk of which is made up of the Precambrian Eleonore Bay succession (Table II). For this reason this depositional area is often called the "**Eleonore Bay Trough**".

The time of the initial accumulation of this huge pile of sediments is unknown, since prolonged denuation of its gneiss pavement (crystallized some 2 b.y. ago in the Scoresby Sund area) preceded the deposition of the basal strata. North of the 76th parallel, however, Eleonore Bay beds were spread over the stumps of the Carolinidian chain—far beyond the boundary of the earliest basin—indicating a post-Carolinidian age for the bulk of the geosynclinal filling. Even so, an immense span of time, some 1 b.y., has to be considered for the development of the geosynclinal tract in Central East Greenland which was completed by Ordovician times, or possibly, in early Silurian.

The Central East Greenland geosyncline is not to be thought of as a simple, basin-like structure but rather as an association of several depressions in differing stages of development which are separated by regions of less rapid subsidence. The geosynclinal prism includes at least four dominant cycles of sedimentation and during this long-continued development, the places of maximum sedimentation shifted many times. Thus, the whole geosynclinal filling is made up of a complex of elongated lenticles. This conclusion refers in particular to

Table II. *The Geosynclinal Pile of Central East Greenland*

LOWER PALEOZOIC	HEIM BJERGE Fm. 320 NARHVALSUND Fm. 460 KAP WEBER Fm. 1,100 CASS FJORD Fm. 230	2,100 m		MIDDLE ORDOVICIAN	
	DOLOMITE POINT Fm. 400 HYOLITHUS CREEK Fm. 210 ELLA Ø Fm. 90 BASTION Fm. 150 KLØFTELV Fm 70	900 m	MIDDLE? LOWER	CAMBRIAN	
PRECAMBRIAN (GROENLANDIAN)	SPIRAL CREEK Fm. CANYON Fm. UPPER TILLITE INTER TILLITE LOWER TILLITE	200–1,000 m		TILLITE GROUP	
	LIMESTONE-DOLOMITE SERIES (Beds 14–20) 1,100 m MULTICOLORED SERIES (Beds 7–13) 1,000 m QUARTZITE SERIES (Beds 1–6) 2,100 m			UPPER	ELEONORE BAY GROUP
	UPPER ARGILLACEOUS-ARENACEOUS SERIES 1,200–3,000 m CALC-ARGILLACEOUS SERIES 0– 300 m LOWER ARENACEOUS-ARGILLACEOUS SERIES 1,200–8,000 m BASAL SERIES (including ophiolites up to 1,000 m) 200–1,400 m			LOWER	
PRECAMBRIAN BASEMENT COMPLEX					
Total thickness of geosynclinal accumulation > 16,000 m					

the initial cycle of sedimentation which produced the *Lower Eleonore Bay Group*, a succession traceable from Scoresby Sund (70° N) to Dove Bugt (77° N). In places, this succession is up to 10,000 m thick. Variations in both thickness and sedimentary facies indicate a period of tectonic unrest and rapid subsidence of the geosynclinal bottom. At the very beginning of this eugeosynclinal condition, a principal invasion of basic magma (*ophiolites*) occurred; it is represented by considerable complexes of greenschists and amphibolites which are closely associated with calcareous beds of the Basal Series. This initial magmatism evidently launched the period of strong geosynclinal subsidence. Whereas the

Basal Series still displays a normal platform sequence (coarse clastics at base, overlain by orthoquartzite-limestone facies and limestone-shale facies), the post-eruption sedimentation indicates a high rate of deposition in an intermittently sinking catchment area (greywackes, impure sandstones, semi-pelites, pelites). In contrast to the early eruptions, the later products of the geosynclinal magmatism are to be found as laccoliths and sills widely distributed, occupying different stratigraphic levels of the pile, but occurring mainly near the top of the Lower Eleonore Bay Group.

With the onset of the second cycle, the *Upper Eleonore Bay Group*, geosynclinal volcanism ceased and sedimentation became much more uniform. The onset of the Upper Eleonore Bay sedimentation represents a distinct change in the depositional environment throughout Central East Greenland. The break at the base of this succession might be called a non-evident disconformity indicating epeirogenetic alterations in both the source area and the subsiding trough. The present outcrops of the Upper Eleonore Bay Group are restricted to a much smaller area (some 500 km) than the beds of the Lower Group. Even so it is astonishing that these formations were laid down with an incredible uniformity over the whole area. The Upper Eleonore Bay cycle produced a transgressive sedimentary succession starting with a thick layer of orthoquartzites which grade into mudstones, limestones and dolomitic sandstones, and finally massive limestones and dolomites. According to this progressive change in lithofacies the Upper Eleonore Bay Group is subdivided into: Quartzite Series, Multicolored Series, and Limestone-Dolomite Series (Plate XIV).

Sediments preserved from cycle three (Tillite Group) and cycle four (Cambro-Ordovician) are restricted to the fjord region between 72° and 74°30′ N. Over this distance of some 250 km, the members of the *Tillite Group* show considerable variation of thickness. At both the base and the top of this peculiar complex of strata are distinct stratigraphical breaks. No angular discordances of bedding are to be seen, but both breaks indicate important regional unconformities, which must represent a considerable period of time.

In contrast, the *Cambro-Ordovician* rocks show again a striking uniformity; they belong to one facies and display very little lateral variation in lithology and faunal content. The Ordovician is overlain with profound angular unconformity by Old Red Sandstone clastics which cross the Lower Paleozoic succession and overstep the Tillite and Eleonore Bay beds.

The areal distribution of these four cycles of sedimentation is shown on Fig. 24. This sketch inevitably leads one to question from which direction the sediments poured into the geosynclinal depression. In the

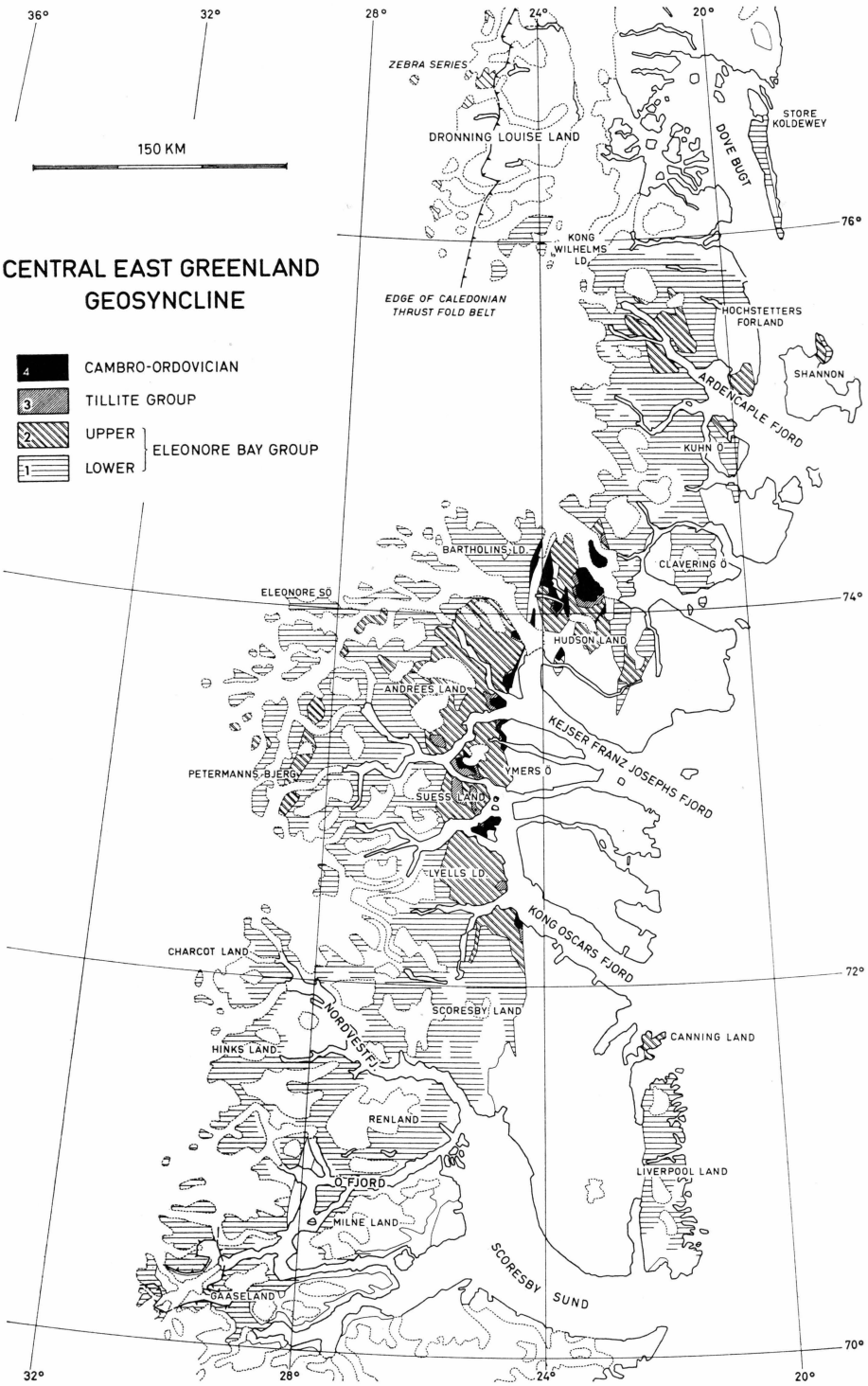


Fig. 24. Areal distribution of sedimentary cycles accumulated in the geosyncline of Central East Greenland.

early period of the geological exploration of East Greenland when this area was still regarded as one great geosyncline[49]), stretching from Scoresby Sund to the Polar Sea, the detritus was considered to have been supplied from the west, that is from the "Greenland Shield". As more facts about the setting of the "Eleonore Bay Trough" came to light, so the question of *potential source areas* became more intricate. Data hitherto available suggest that a substantial part of the Lower Eleonore Bay Group was derived from the east and/or the north, that is, from a hypothetical borderland, the continuation of the Carolinidian chain now submerged in the Greenland Sea. The Upper Eleonore Bay Group with its uniform development over a north-south stretch of around 500 km had presumably its sources in the west; likewise the same is true of the psammitic strata at the base of the Paleozoic. The Tillite Group, on the other hand, shows evidence of sediment transport from both north and south. Hence the history of this depositional area is long and varied, and we do not actually know much about it.

Even the widely accepted two-fold division of geosynclinal structures into the miogeosyncline, adjacent to the craton and free of igneous activity, and the eugeosyncline, associated with volcanics, is rather difficult to apply to the environments in Central East Greenland. Apart

[49]) As a result of reconnaissance flights made in 1933 over Kronprins Christian Land and Mylius-Erichsen Land, LAUGE KOCH (1935 a) presumed that 'dark-grey shales' and 'limestone-dolomite series' (today known as Hagen Fjord Group and Cambro-Silurian) could be correlated with the upper part of the "Eleonore Bay Formation" in Central East Greenland, although the "Thule Formation" of Mylius-Erichsen Land undoubtedly embraces more than the Quartzite Series of the Eleonore Bay succession. Koch considered then the "Thule Formation" to be the *littoral* facies of the geosyclinal "Eleonore Bay Formation".

KOCH always considered the "*East Greenland Geosyncline*", a coherent belt stretching from Scoresby Sund to Kronprins Christian Land, to be entirely separate from what he then called the "Smith Sound Geosyncline" *i.e.* the *Franklinian Geosyncline* in North Greenland. In his thesis (1929 b) he had already stressed at length the different developments of these two basins of sedimentation (In East Greenland a huge Precambrian sequence followed by marine sedimentation up to Middle Ordovician. In North Greenland Precambrian sediments were found to form only a small part of the succession; the main thickness was made up of Ordovician and Silurian strata).

E. NIELSEN's sledge journey to Kronprins Christian Land in the spring of 1939 confirmed LAUGE KOCH's early ideas about the structure of the Caledonides in Northeast Greenland. However, NIELSEN (1941, pp. 26–27) doubted KOCH's concept of the strict separation of the geosynclines of East and North Greenland. He thought it more probable 'that the East Greenland geosyncline follows the shape of the Greenland Block and therefore swerves westward in an even curve and has its direct continuation on the North Greenland geosyncline' (*l.c.*). This question remained unanswered for another two decades, until the discovery of the late-Precambrian cross-structure, the "Carolinidian Belt" (HALLER, 1961 a; L. KOCH, 1961).

from the initial cycle of eugeosynclinal sedimentation, however, the accumulation of fine to coarse clastics and carbonates of the Upper Eleonore Bay Group, the Tillite Group, and the Cambro-Ordovician generally shows a miogeosynclinal aspect.

5. THE CALEDONIAN OROGENY

The East Greenland Caledonides[50]), initiated in Silurian times, run roughly parallel with the coast line. The structure pattern of this considerably denuded mountain belt is displayed over a distance of 1,400 km. Map Sheets 1, 2, 3 cover some 1,100 km of this total length of exposure. The fold belt developed during three periods of tectonic activity which formed an unbroken sequence in the orogenic cycle. On the basis of rock and mineral ages as well as of the present standard time scale[51]) applied to stratigraphically dated events, the time indices of this structural succession are approximately as follows:

(A) Caledonian main orogeny: 420–400 m.y. (Silurian)
(B) Late Caledonian spasms: 400–350 m.y. (Devonian)
(C) Minor succeeding episodes: 350–270 m.y. (Carboniferous)

This tentative scale outlines the astonishing longevity of the tectonic unrest. We have to picture, however, that the major orogenic events are restricted to Siluro-Devonian times, that is an interval of some 70 million years. Also, the great revolution that virtually piled up the principal mountain belt developed in a comparatively short period after the onset of diastrophism.

The *main orogeny*, launched by deep-seated mobility, affected the whole length of Greenland's east coast north of the 70th parallel. This event, with vast regional metamorphism, reached its climax towards 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.

The secondary *late spasms* generally produced folding related to regional compression and the upward injection of late-orogenic palingenites. The affected areas were quite restricted compared with the area covered by the main orogeny, since they occurred mainly within

[50]) Cf. remarks on the terminology "Caledonian" (HALLER and KULP, 1962, pp. 68–73).

[51]) KULP, J.L. (1961). Geologic Time Scale, pp. 1105–14, Science, **133**, No. 3459, (Washington D.C.).

an intramontane depression which acted as a catchment basin for Old Red Sandstone detritus. These Devonian events arose during an interval of 20 to 50 million years.

Concluding pulses continued for another interval of some 100 million years until the entire belt was completely stabilized and finally relaxation set in. These tectonic events, interpreted merely as *minor succeeding episodes* of the whole orogenic cycle, 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, occurred in an area strictly confined to the southern compartment of the Old Red Sandstone basin structure. Several late Caledonian fracture systems were renewed in Upper Carboniferous and Lower Permian times when Central East Greenland was still the site of continental deposition. This is in contrast to Northeast Greenland, where the sea transgressed across the truncated fold belt in Upper Carboniferous times. In the south, the continental Carboniferous as well as the coarse clastic Lower(?) Permian deposits are still to be considered waste products (molasse-type sediments) of the Caledonides, which were only peneplaned when the area became a part of the Upper Permian sea.

A. Caledonian Main Orogeny

(Called "old" Caledonian folding, Silurian)

In the 1,400 km long tectogene accessible today, the structural patterns of the main orogeny are entirely different from region to region. The style of deformation not only varies across the fold belt, but also changes distinctly along the orogenic axis. In both cases it is the contrasts in orogenic deformation and mobility between different units which produced this variation.

Interaction of basement and cover

If we follow the course of the mountain structure from south to north, we can observe a tectonic variation, which was apparently controlled by the thickness of the supra-crustal pile affected by the orogeny:

When the cover was very heavy and the bulk of the sediments acted stiffly, as was the case with the 16,000 meters thick geosynclinal pile in *Central East Greenland*, a folded chain developed without remarkable crustal shortening. Continuous structures with general constant direction prevail. Here, a considerable part of the superficial cover, combined with its ancient crystalline pavement, underwent rock-transformation *in situ* by orogenic heat and granitizing agents ('migmatite front', Fig. 25).

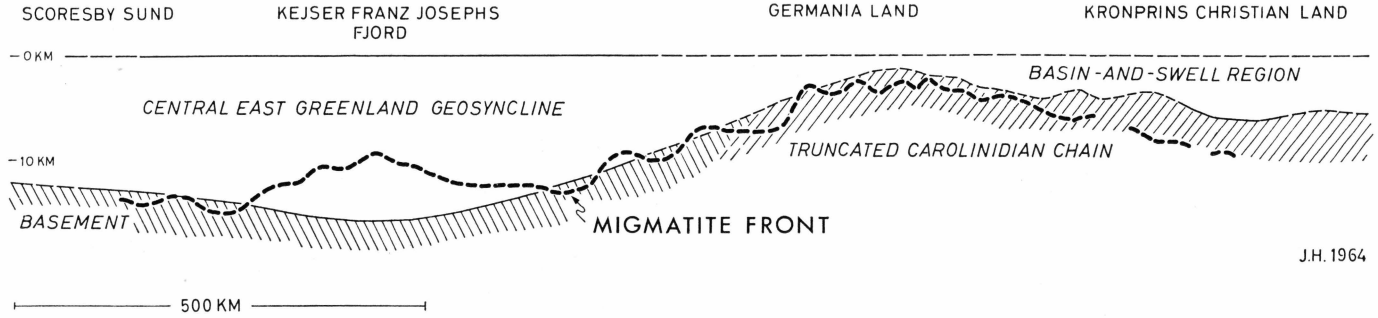


Fig. 25. Diagrammatic section showing the vertical distribution of basement and cover at the beginning of the orogeny. The plotted position of the Caledonian migmatite front is inferred from field evidence.

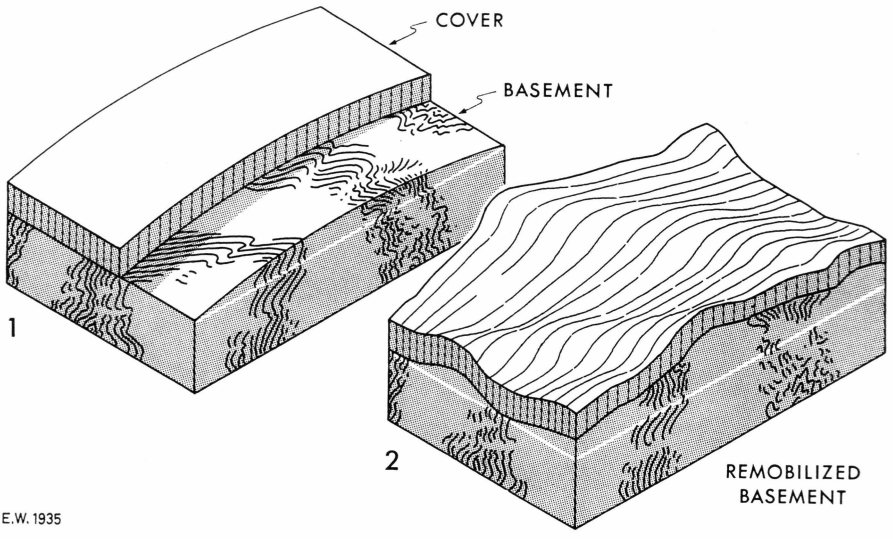


Fig. 26. Diagram showing interaction of basement and cover during an early stage of the Caledonian main orogeny in Central East Greenland. The internal structure of the basement became remobilized under stationary conditions: (1) Structural relations prior to orogeny; the truncated basement, as a rule, consists of steeply inclined zones containing greater and lesser amounts of granitoid material. (2) Remobilization of the stationary host by the orogenic action: Temperature and pressure reached certain limits and the ancient granitoid cores became capable of movement. Transport of material took place, contacts began to move, and new migmatites arose in the old basement. Thus, the internal structure of the basement received new life by means of a selective regroupment. Differential movement, acting from the remobilized basement, also affected the cover. As a result, the "embryonic" deformation pattern which developed in the cover inherits the old trends. This pattern can easily be oblique or even transverse to the trend of regional arching along the orogenic axis. (After C. E. WEGMANN, 1935, p. 339).

Where there had been a thin stratified overburden, linear structure elements, caused by thrust movements, are predominant. This is the common case in *Northeast Greenland.* Here, the basement is incorporated in the thrust-fold structure in the form of stiff plates and wedges. North of the 76th parallel, the active Caledonian structural elements, linked with migmatitic rejuvenation, reach the surface only in strips. To a large extent, the fronts of orogenic mobilization and metamorphism remained within the ancient basement complexes, with the result that several areas of Northeast Greenland were not subjected to Caledonian regional metamorphism at all or were merely retrogressively overprinted.

In the Silurian, when orogenic action set in, the pavement of the Central East Greenland geosyncline was much more deeply buried than that of the northern basin tracts. Although in the south, deposition had ceased perhaps as early as Upper Ordovician, the base of the great geo-

synclinal pile lay at least some 10,000 meters deeper than that of the northern basin-and-swell region.

Although *geosynclinal depth* in Central East Greenland amounted to some 16 km, it should be added, however, that there are no signs of a metamorphic variation which could be related to such depth variation. Thus, the pattern of regional metamorphism and the development of migmatite belts are to be considered as incidents of the Caledonian orogeny proper, even though the pre-orogenic sedimentary environments had some influence upon the layout and style of the tectonic pattern, which, in turn, guided the advance of the wave of regional metamorphism.

For various reasons it is suggested that the main orogenic adjustments settled into the northern and southern regions under different physico-chemical conditions, related to the depth of burial of the basement: In the north, strong deformation preceded the chemical breakdown, thus affecting a mainly rigid pavement which was thinly to moderately covered by sediments. As a result, long narrow zones of granitization and belts of mobility were formed, largely following the general trend of the whole mountain chain. This pattern is in complete contrast to that produced by the deformation of the heavily loaded pavement in Central East Greenland. There, the initial stage of the orogeny was seemingly dominated by heat action, so that all subsequent deformative movements largely caused an extensive reactivation process and selective regroupment of the basement architecture (Fig. 26). In this way, the deep-seated Caledonian structures partly inherited the internal structure of the Precambrian basement block. Yet, these ghost structures, though striking transverse in places, had no noticeable influence upon the general N–S trend of the mountain belt.

Differing tectonic styles of the deeper and the shallower parts of the fold belt

1) Central East Greenland.

Most spectacular vertical sections across the main Caledonian architecture are to be found in Central East Greenland. In the huge pile of mainly thick-bedded, stiff strata of the geosyncline (cf. Table II), the orogeny gave rise to large-scale disharmonic folding. The decisive factor of this basic pattern of Caledonian adjustments is the behavior of the highly mobile fundamental structure of granotoid composition, called the **infrastructure.** Infrastructural conditions arise by the advance of the migmatite front from below to involve both basement and geosynclinal filling alike. The migmatitic complexes are overlain by a broadly

folded mantle of sediments, called the **superstructure**, which underwent only weak metamorphism. The elongate open folds of the sedimentary superstructure reflect more or less faithfully the deformation of the deeper-seated rock units. Thus, the growing mountain belt was split into different levels with different degrees of intensities of deformation. For this multiple type of tectonic event WEGMANN (1935b, p. 332) introduced the term "**stockwerk**"-**folding**: in German 'stockwerk' refers to floors, storeys in a house.

Fig. 27 diagrammatically represents the 'stockwerk' tectonics in Central East Greenland. It shows how difference in plasticity between infrastructure and superstructure led to disharmonic folding on an immense scale. In the main Caledonian act, the most varied structural shapes came into being piled one on top of the other, and in a number of ways it can be proved that the movements in each tier were largely synchronous. Each level is typified by definite rock-types and tectonic elements, reacting to the penetrative movements in different ways. Causally, all tiers are closely linked but nevertheless noticeable discrepancies occur, particularly with regard to structures. The discrepancies may be so great that the fold axes of one level lie even at right angles to those of the next. An example of such a rare state of affairs can be seen in the area around Kempes Fjord (72°50′ N), where inherited basement structures disposed the layout of the Caledonian migmatite 'stockwerk'.

Though it is a general feature of this type of mountain structure that orogenic movements considerably increased with depth, it is self-evident that a zone of extreme contortion was established between the flow folds of the migmatitic lower tier and the sedimentary upper tier, which was deformed in a relatively stiff condition. This transitional **zone of detachment** greatly varies in thickness and style of deformation from place to place. Contorted lamellae and ptygmatically folded hypermobile derivatives of the migmatite-soaked substratum are common. These shoots, in turn, led to an extreme state of heteroplasticity in this domain of detachment. Thus, shear structures, incongruous drag folds,

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Fig. 27. Three-dimensional representation of a '*stockwerk*' folded orogeny showing three tiers: In the deep-seated core, the infrastructure (1), all rocks were transformed into granitoid types. The migmatitic centers welled up into bulges and took part in peculiar flow movements. The superstructure (3) consists of low-grade or non-metamorphic sediments. In contrast to the plastic deformation of the infrastructure, this tier acted stiffly; its open folds are a weak reflection of the powerful movements underneath. The difference in plasticity between (1) and (3) led to a zone of disharmonious detachment. This zone (2) varies greatly in thickness and style of deformation.

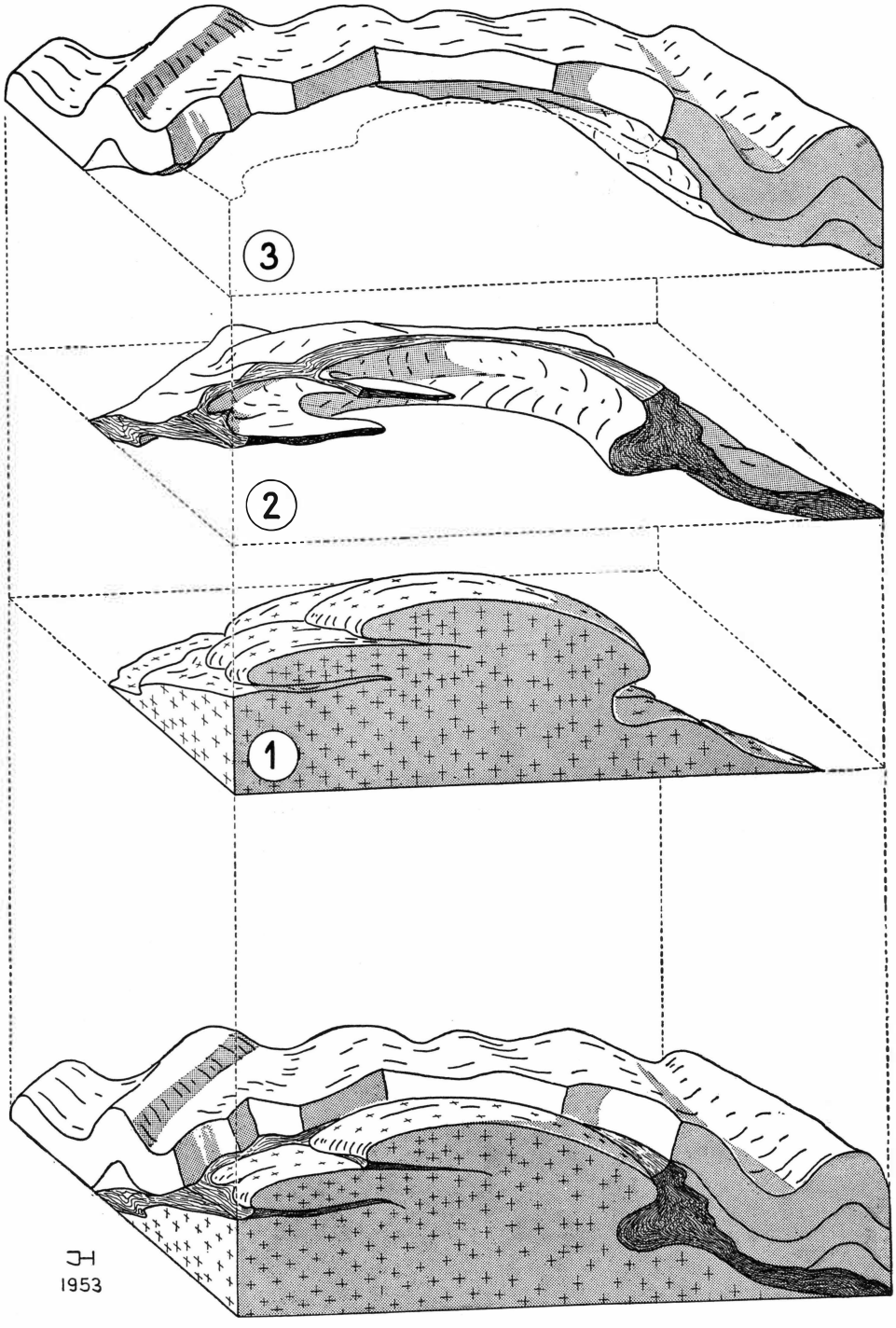


Fig. 27.

and tectonic thinning and thickening of incompetent rock material are further characteristics.

The zone of detachment, separating the migmatitic infrastructure from the non-migmatitic superstructure, mainly contains complexes of originally pelitic strata. As a rule, these beds were highly metamorphosed forming mica-schists, often kyanite-bearing. Thus, the wave of regional thermometamorphism, which is closely related to the formation of the migmatitic infrastructure, passed through the zone of detachment and ascended for hundreds or thousands of meters into the superstructure (cf. HALLER and KULP, 1962, p. 39). From this it becomes evident that, tectonically, large regions of metamorphosed sediments must be counted as part of the sedimentary superstructure.

There are petrogenetic gradations from the migmatitic infrastructure to the metamorphic cover rocks, and sometimes it is rather difficult to decide the position of the outer edge of an infrastructural unit. In addition, the zone of detachment varies from some 150 to 1,500 meters in thickness, mainly depending on the kind of meta-sedimentary rocks at the outer edge of the infrastructure. It should be stressed, however, that the detachment was not controlled by a distinct metamorphic facies, though it developed mostly at the immediate outer edge of the migmatite complexes. This is illustrated, for example, at the cliff of Maalebjerg (Western Andrées Land) shown on Fig. 28.

Over wide areas of Central East Greenland, Caledonian migmatization advanced thousands of meters into the Eleonore Bay succession. Infrastructural conditions affected both the basement and the geosynclinal filling (cf. Fig. 25). The basal unconformity became blurred so that the granitized sediments and their reworked basement rocks were welded together without a seam. Thus, in this part of the East Greenland Caledonides the deep-seated fundamental structure involved a considerable amount of sedimentary material which underwent transformation *in situ*. I point to this fact to emphasize once more that the partition of the Caledonian architecture into a number of tiers is the product of the orogenic activity. 'Stockwerk'-folding is a tectonic feature and should not be confused with the stratigraphic concept of basement and cover which refers to the conditions prior to the mountain building cycle.

Style of suprastructural folding. In Central East Greenland, open northerly trending anticlines and synclines dominate the tectonics of the superstructure. Their formation was apparently mainly due to *vertical* movements. In the underlying metamorphic and migmatitic series, indeed, related movements were traced to be pre or paracrystalline with respect to most rock components. The paracrystalline formation



Fig. 28. Aerial view of Maalebjerg which rises as a conspicuous cliff some 1,000 m over Gerard de Geer Gletscher. The rocks to be seen are epimetamorphic Eleonore Bay beds of the Basal Series. At the left foot of the cliff, migmatitic and augen gneisses occur. The overlying light-colored metaquartzites in center still show structural affinity to the infrastructure so that the *zone of detachment* entirely developed in a pelite-marble complex of low grade regional metamorphism. The superstructure (right and top part of the cliff) includes light-colored marbles and brown quartzitic schists. — Air-phot. E. Hofer, 1950.

indicates a close connection genetically between these fold elements and the rise of the migmatite front. When migmatitic tumors and bulges developed in the infrastructure, the sediments of the superstructure were metamorphosed in places and thrown into open folds weakly reflecting the powerful and active movements underneath. The launching movements were mainly vertical; tangential forces only came into effect locally.

In the fjord and nunatak regions of Central East Greenland (Map Sheet 3), the fold elements of the superstructure have a general N–S trend. The shape, however, varies considerably along their length, pronounced anticlinal structures alternating with wide, open warpings (Fig. 29, Plate XV). It is not always easy to follow up the axes of this open folding. In this respect the Tectonic Map may, perhaps, give an erroneous idea. For correct interpretation I refer to the structural contour map of the area (Plate XLI). On the basis of this map a maximum of stratum shortening due to superstructural folding is to be seen on western Ymers Ø. Having analyzed the folding of that area, EHA (1953, p. 91) estimated a shortening of 5.3 per cent[52]), that is to say for a section 25 km in length the shortening is on the average 1.3 km. However, this amount of shortening, obtained from the Antarctics Sund section, is a result of both an original main Caledonian folding and a late Caledonian tightening and accentuation of the principal pattern. EHA was not able to differentiate these events in figures, but he hold more than half of the amount of the total shortening due to late orogenic forces acting from the east (see p. 120).

Style of infrastructural folding. Infrastructural conditions arise through the process of migmatization and granitization. The top of the infrastructure represents the level reached by the **migmatite front**, *i.e.*, the synorogenic wave of ultra-metamorphism which passed through the rocks leaving a gneiss and granite zone behind it. In relation to 'stockwerk' tectonics, an important feature is that the migmatite front ascended unequally and selectively. This characteristic, satisfactorily reported from various orogeny structures, is well displayed in the East Greenland Caledonides. It can be seen that both the cores of granitization and their related zones of regional metamorphism cut across the stratigraphy. From place to place, however, the specific structural tiers developed at quite different positions in the stratigraphical column or within the basement (cf. HALLER and KULP, 1962, p. 39).

[52]) The open nature of the folding in this superstructure becomes evident from a comparison with other fold belts. In the Jura Mountains, a shortening of 20–30 per cent is obtained, in the Swiss Alps with their nappe structures this reaches 50–75 per cent (J. CADISCH, 1942, Verh. Natf. Ges. Basel, *54*).



Fig. 29. Aerial view of the southward plunging "Marginal Anticline" at Ella Ø. The fold structure is cut by late orogenic faults (f). The folded strata include: 8 = Limestone-Dolomite Series, 9 = Tillite Group, 10 = Cambrian, 11 = Ordovician; the latter being overlain with angular unconformity by Old Red Sandstone = 12. — Geodætisk Institut Eneret, Nr. 638/9,920.

Activated by the supply of orogenic heat and the inflow of material, the growing infrastructure behaved as a series of highly mobile and active elements, forming irregular flow-folds. The foci of migmatitic activity expanded to produce vertically directed syntectonic upwellings. The induced compartments grew into bulges and offshoots of different shapes and size orders. According to the areal extension of individual infrastructural units we can distinguish between *regional doming* and *locally upwelled masses*. The regional swellings are of circular to ellipsoid outlines more than 20 km in diameter. The smaller upwellings have more the characteristics of recumbent anticlines forming an overlap of from half a kilometer to a few kilometers. In a paper of 1955 dealing with the "Central Metamorphic Complex"[53]), I have classified these infrastructural bulges into five types according to their field-geological aspects:

(i) *Migmatite domes*: concentrically layered dome-like bodies spreading in all directions; they may occupy the kernel of a regional bulge (cf. Figs. 5 and 6).

(ii) *Migmatite 'foreheads'*: tongue-shaped migmatite bodies in the cores of overturned or recumbent upfolds.

(iii) *Migmatite sheets*: large nappe-like migmatite bodies caused by extensive lateral welling. They are asymmetrical and feature considerable overlaps of up to 25 kilometers. Regional thrusting is probably of no importance in their formation. The migmatite body, which welled out horizontally is the product of independent flow movements initiated by granitizing agents rising vertically. The direction of expansion apparently depends on the original setting and bedding of the sedimentary mantle.

The emplacement of sheet structures contrasts with the relatively static development of a dome-like bulge; the formation of a sheet involved more dynamic processes and stepwise enlarging, originally launched by vertically directed forces.

(iv) *Migmatite mushrooms*: migmatite bodies which display expansion in two or more directions, forming conjugate flow folds, mushroom-shaped in cross-sections (Plate XLII). Horizontal offshoots and inrolled folds developed from a vertical root mass, the internal structure of which, however, showing horizontal to slightly plunging fold axes. These mushroom-shaped bodies are closely related to the nappe-like sheet structures (iii).

(v) *Migmatite complexes*: cases of intricate coalescence of migmatite bulges of various types. A migmatite complex consists of a crowd of small steep-sided upfolds, foreheads, and minor sheet and mushroom struc-

[53]) Belt of Caledonian metamorphic rocks spreading north and south from inner Kejser Franz Josephs Fjord.

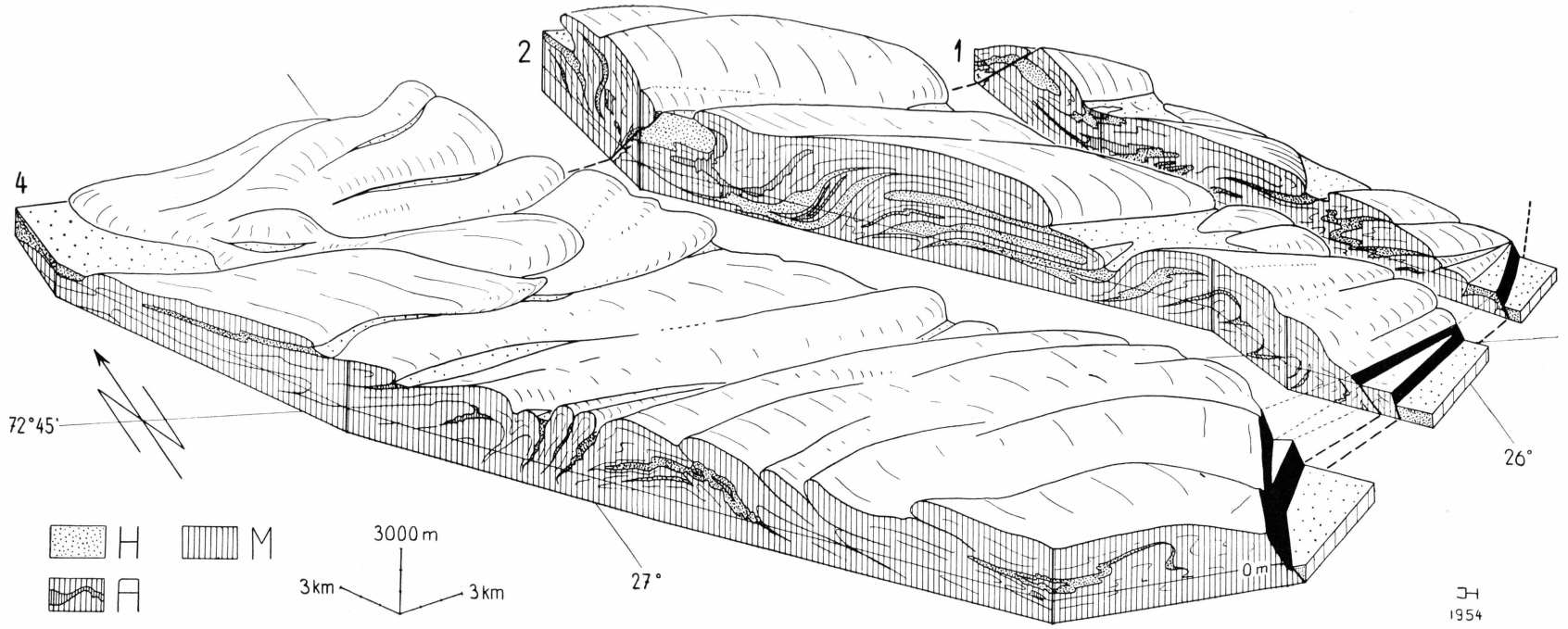


Fig. 30. Block-diagram showing the "*Gletscherland migmatite complex*".

The diagram omits all the covering rocks of the superstructure. The horizontal and vertical scales are equal; the coordinates at the base indicate that the block is not pulled apart. Section 2 corresponds in part of the exposures to be seen along the eastern wall of outer Dickson Fjord. (H = metamorphites, M = migmatites, A = amphibolites). Cf. J. HALLER, (1955, pp. 95–111).

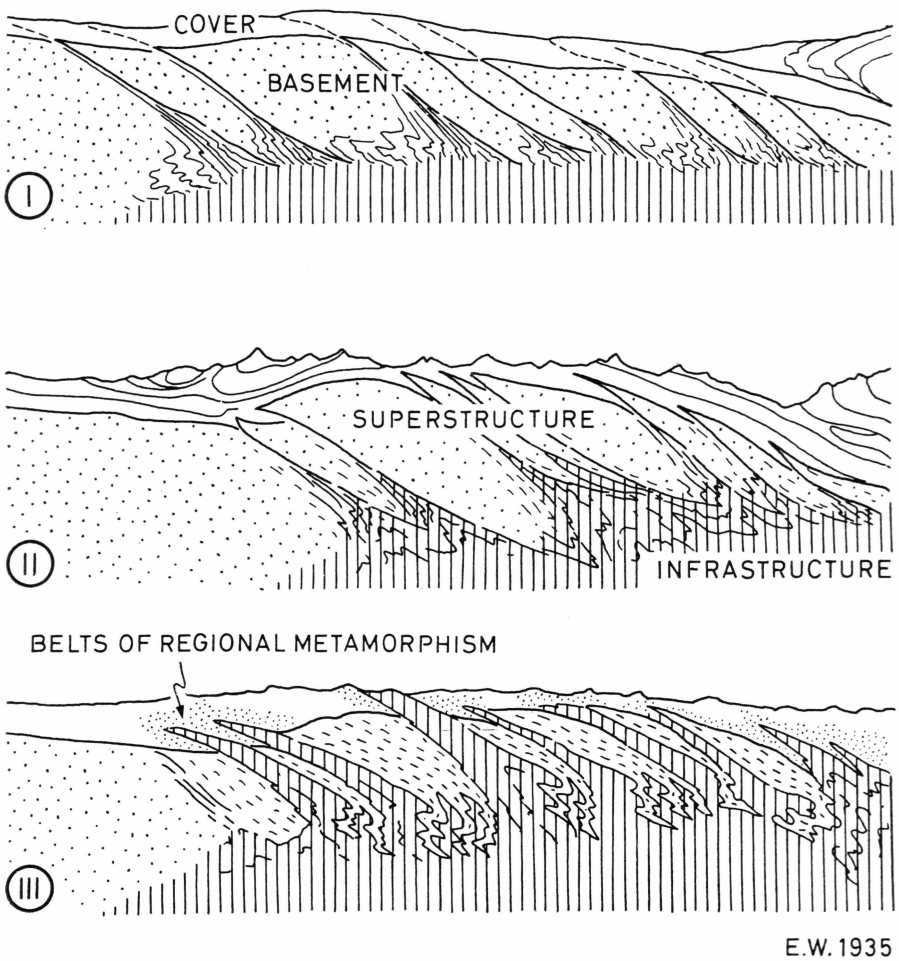


Fig. 31. Consecutive sections showing a '*stockwerk*' architecture where the migmatite front became stuck within the basement complex. This scheme, adapted from C. E. WEGMANN (1935, p. 337), illustrates quite well the type of main Caledonian tectonics in Northeast Greenland, where the basal pavement is incorporated in the thrust-fold structure in the form of stiff plates and basement wedges, and where zones of migmatitic rejuvenation reach the surface only in strips.

tures. The individual patterns are peculiarly interwoven owing to lack of space. As a combination of several minor offshoots the complex constitutes a form of regional doming (Fig. 30).

The up-welling of the migmatite body caused a powerful interplay, in which the individual units impeded, overlaid and penetrated each other in competition for space. There was an intermittent growth of infrastructural units which emplaced themselves step by step, all starting out from a large-scale basement remobilization. A considerable part of the sedimentary cover became successively involved in these movements and was finally subjected to granitization, too. Among the Eleonore Bay beds involved only the basal quartzite-limestone succession, associated with ophiolites, can be followed across most of the domain of Caledonian migmatization, although then in the form of high-grade metamorphites (Plate XVI). These characteristic horizons provide reliable marker-beds bringing out the intense contortion within the infrastructure. Bands, wedges, lenses, or intensely contored masses of those rocks make possible the recognition of the shape of individual migmatite units and the infrastructure as a whole. In addition to the structural aspect, these basal marker beds allow a rough estimate about the portions of obliterated basement gneisses and the amount of Eleonore Bay beds incorporated in the migmatite 'stockwerk'.

Section (I) shows the softening-up of the basement block at some depth and the early formation of the migmatitic infrastructure. Flow movements deep down continued in the form of shearing into higher levels where the basement rocks remained rigid and were split up into strain sheets.

In section (II) migmatization and mobilization advanced selectively upwards usually following the pattern of shear zones. Slices and wedges of the basement rocks moved differentially and caused related thrust and fold structures in the cover.

Section (III) represents a final stage of this semiplastic to rigid shearing of basement rocks with a subsequent selective metamorphic action. Here migmatitic rejuvenation, largely confined to mobile strips, even advanced into the sedimentary cover producing belts of regional metamorphism. A similar relationship occurs with the metamorphic overprint of basement wedges between the mobile strips. There, as a rule retrogressive stages of metamorphism resulted. Section (III) clearly demonstrates how zones of infrastructural characteristics overlap superstructural compartments producing a multiple type of '*stockwerk*' arrangement.

2) Northeast Greenland.

On previous pages I pointed to the difference in tectonic style in Central East and Northeast Greenland. Among the factors affecting this, attention was mainly called to the contrast in thicknesses of the stratified overburden and to the different modes of basement deformation. With regard to the ascent of the Caledonian migmatite front—as tentatively shown on Fig. 25—it becomes evident that in Northeast Greenland, that is in the Germania Land region and northwards, the concept of 'stockwerk' tectonics is still applicable. There exists an analogous pair of principal 'stockwerks', that is the subdivision into *infrastructural* compartments, referring to Caledonian migmatization superposed on gneissose basement rocks, and a *suprastructural* mantle, where the affected basement rocks remained rigid enough to be sheared and broken. Here, however, the contrasts in plasticity and in style of folding between compartments involved in the infrastructure and those belonging to the superstructure are much sharper than at the top of the migmatized Eleonore Bay beds in Central East Greenland. The type of 'stockwerk' structure which was created by a partial reworking of the basement block is fairly well pictured by three sequential sections published by E. WEGMANN (1935b). Although this diagram, redrawn on Figure 31, is deduced from structural patterns mainly observed in the Karelides, it fits precisely the principles of tectonics displayed in Northeast Greenland. The diagram clearly shows how migmatization and mobilization advanced selectively upwards, resulting in an intricate interfingering of mobil migmatite sheets with resistant basement wedges. Plate XVII illustrates the zone of junction of the actual Caledonian infrastructure and the superstructure in the reworked basement complexes of southern Dove Bugt. The two tiers not only vary in style of deformation (plastic folding versus semi-plastic to brittle distortion) but also in the strike of their internal structures. The resistant basement rocks, although pulled apart into shear lenticles, still include a Precambrian fabric.

On the islands and peninsulas of Dove Bugt, the Caledonian infrastructural belts, with a NE–SW trend, are overprinted on Carolinidian gneiss masses which lie transverse to this direction. Cross-folding with zonal selection led here to an assemblage of resistant and mobile rock masses side by side. The mobile strips of Dove Bugt, however, form ingredients of the active central structure, which backs up the westward travelled Caledonian allochthon, exposed in Dronning Louise Land. North of Dove Bugt, in Germania Land, the tesselated pattern is entirely lost in an unbroken block of Carolinidian gneiss.

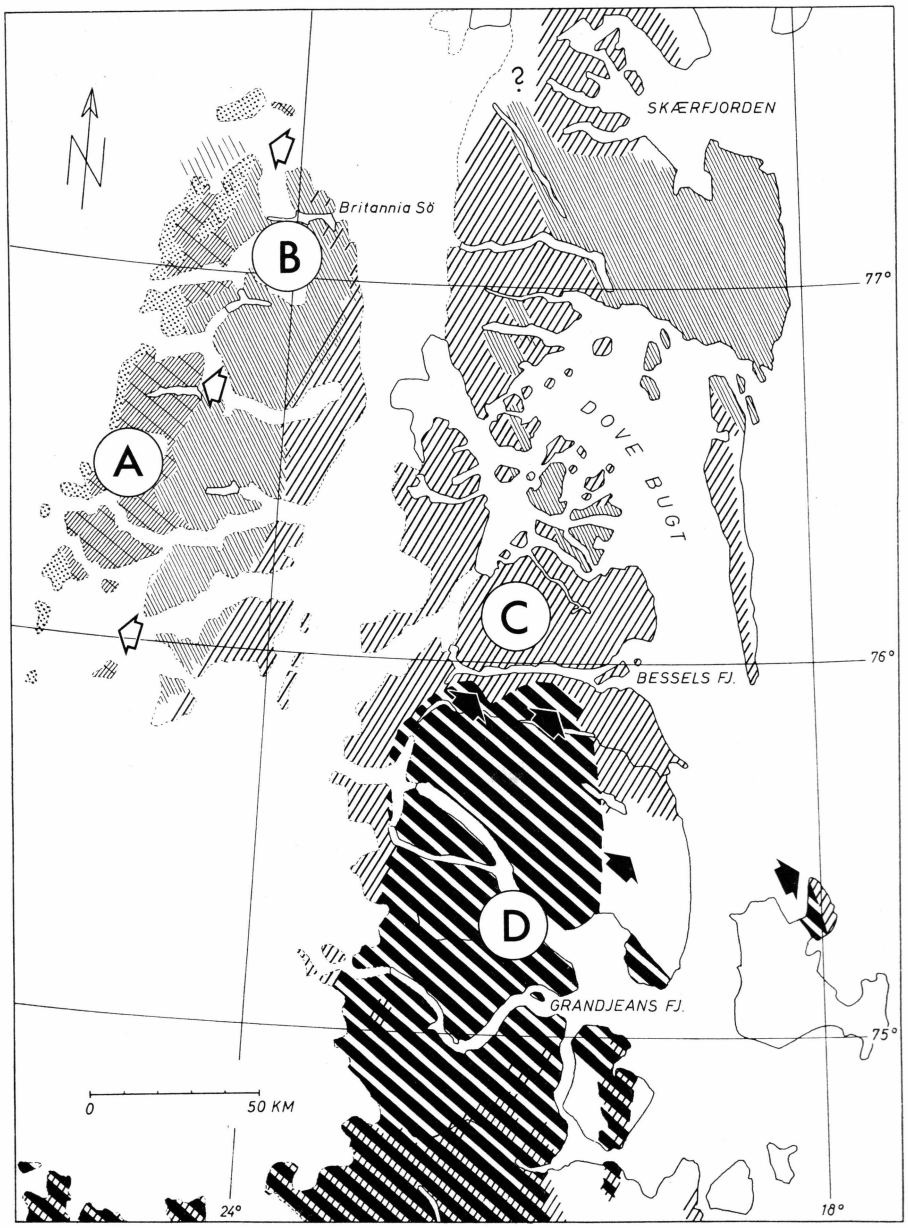


Fig. 32. Structural patterns of the East Greenland Caledonides between lats. 75° and 78° N. The direction of shading in each area corresponds approximately to the strike of the structural unit concerned. (A) Pre-Groenlandian Basement, overlain by Precambrian sediments (dotted areas); (B) Carolinidian metamorphic complexes, caught up in the Caledonian folding; (C) structures of the Caledonian main folding; (D) late-Caledonian structures. Arrows signify thrusts (white — Caledonian main phase; black — Caledonian late phase). — After J. HALLER (1957 b).

Fig. 33. Small island at the mouth of Hellefjord (Dove Bugt, 76°50′ N) showing blocks of resistant basic rocks in a polyphase crystalline complex, soaked with Caledonian mobilizers (white pegmatoid material). — Air-phot. W. DIEHL, 1955.



Fig. 34. Mode of reactivation and refolding in banded, leucocratic gneiss. North coast of inner Bessels Fjord. — Phot. J. HALLER, 1955.

The Dove Bugt area thus consists of a mosaic of tectonic fields of different ages (Fig. 32). The internal structure of the partially mobile zone of fold interference clearly betrays the style of the new folding in the Dove Bugt—the deformative processes preceded the chemical transformations of the rock material. Supplies of heat and matter from the depth did not affect the shattered ancient crystalline complex uniformly. The establishment of mobile zones was essentially guided by the spatial position of early fracture lamellae. In that way, any petrological and structural rejuvenation of the substratum took place most selectively. The tectonic environment displayed in Dove Bugt is a structural rearrangement controlled by the grade of mobility of the reworked gneiss complexes. This process of structural differentiation led to the concentration of resistant and mobile rock masses in adjacent fields.

Where Caledonian granitization was most intense, the old gneiss material was completely remobilized and newly folded so that no remnants of the old structures remained. The basic rocks were most able to resist these processes of soaking and assimilation, and are now frequently found as isolated fragments, boudins, and irregular masses (Fig. 33). Their shape and position enable one to estimate the degree of deformation and remobilization in the mobile zone.

Parts of the *old crystalline* complex which remained resistant occur as masses 10 meters to 10 kilometers in size. The large masses (covering areas greater than 1 sq. km) have only been reactivated and refolded around their margins. An example from southern Dove Bugt illustrates this type of overprinting which occurs on a large scale (Plate XVIII, A). The photograph shows the steep plunge of the structures at the periphery of a resistant field with subhorizontal axes (Carolinidian fold system). In the marginal zone as the degree of Caledonian remobilization increased, the axes of the gneiss have been rotated into steep position.

Areas of subhorizontal tectonics with steep axes around the periphery have been described in a number of basement complexes. From my experience in the East Greenland fold belt it is suggested that, in general, steep axial tectonics is indicative of reworked pre-existing crystalline blocks, though the rock material may have been completely recrystallized.

In the Dove Bugt area, similar relationships are to be observed on a small scale as well. A majority of the smaller relic masses consists of melanocratic gneisses and amphibolites. All relics which have remained intact possess the same strike, the strike of the Carolinidian pattern. A few masses smaller than of the order of 10 meters have been rotated from their original strike by the new folding. A type of superimposition which is widespread on a small scale is shown on Plate XVIII, B. The old mass consists of melanocratic gneiss and the end has been plastically deformed. The B-axis of the old gneiss lies almost perpendicular to the lineation in the granitized and rejuvenated adjacent rock.

The two directions, however, will not be so clearly distinguished where leucocratic gneisses were subjected to refolding. In that case an intricate interference pattern of small scale folds refolded under plastic condition may have been produced. An example of intensely contorted banded gneiss is shown on Fig. 34.

South of Dove Bugt, much larger spaces were subjected to infrastructural conditions. There, the mobile material could move *ejectively* (*i.e.* forced upwards from below). An early stage in this process of movement is shown on Fig. 35; this type of upfolding, however, is closely analogous to the formation of tight bulges such as mentioned from the Gletscherland migmatite complex (cf. Fig. 30) of Central East Green-



Fig. 35. Migmatites (F) of the mobile Caledonian infrastructure ejectively forced into a tight vertical fold structure, some 500 meters in height. (P) late orogenic pegmatites. Northern wall of outer Bessels Fjord (76° N). — Air-phot. W. DIEHL, 1955.

land. Where this process advanced, the few remaining resistant masses of the old rock have been partly buried by the outgrowths of the young mobile zone. This is the case for example at the west side of Soranergletscher (Plate XIX), where a cross-fold resulting from this ejective process is exposed. The lower part of the 800 meters high mountain side consists of untouched old material retaining pre-Caledonian structures. In the upper part, a tongue-like upwelling from the infrastructure ("C") can be seen. The axis of this ejective flow fold subtends a small angle to the cliff face and lies perpendicular to the axis in the buried mass of old gneiss. Both systems have subhorizontal axes.

Towards the north and northeast, the Dove Bugt interference pattern disappears and in Germania Land pre-Caledonian structures are predominant. There, a continuous transition from overprinted to untouched old crystalline rocks takes place. The front of Caledonian reactivation plunges northwards and the old rocks outside this aureole were transposed and fractured in semi-plastic condition. The zone of migmatitic flow folds lies below the present level of exposure, and its



Fig. 36. Lenticular acute-angled flow folds, originated from a plexus of shear lenticles subsequently subjected to infrastructural condition. Western cliff of Syttendemajfjorden (A. S. Jensen Land, 76°15′ N). — Air-phot. W. DIEHL, 1955.

overlying mantle of shear belts, *i.e.* the superstructure, dominates the Caledonian pattern. The blocks and fragments resulting from this suprastructural fracturing and shearing form wedge-shaped, plate or spindle like bodies (Plate XX) whose long axes lie perpendicular to the direction of maximum stress, so that their formation is closely related to that of folds. These shear lenticles and fracture blocks are to be classified as B-tectonites on a large scale. The block axes are largely parallel to the flow-fold axes of the deeper levels; concordant interfingering is clearly to be seen at many places. Moreover, with Figure 36 and Plate XXI two examples from the Dove Bugt region are shown in order to illustrate that in places the plexus of shear lenticles described above became subsequently involved in Caledonian infrastructural conditions as well. Migmatization ascended into the plexus welding the fracture pattern into a system of characteristic large-scale acute-angled folds.

In the area of Skærfjorden (77°30′ N) a whorl-like bulge some 60 km in diameter, emerges as the northernmost regional doming of the Caledonian migmatite front. The rock material consists throughout of obliterated, reactivated and recrystallized old gneisses of deep-seated character. Originally they may well have been part of the pre-Groenlandian basement but then were modified by the Carolinidian orogeny. Caledonian migmatite flow folds underlie and overlie the semi-plastically deformed rock units. Zones of fluidity and complete obliteration alternate with packets of merely softened and mechanically broken-down ancient country rocks (Fig. 37).

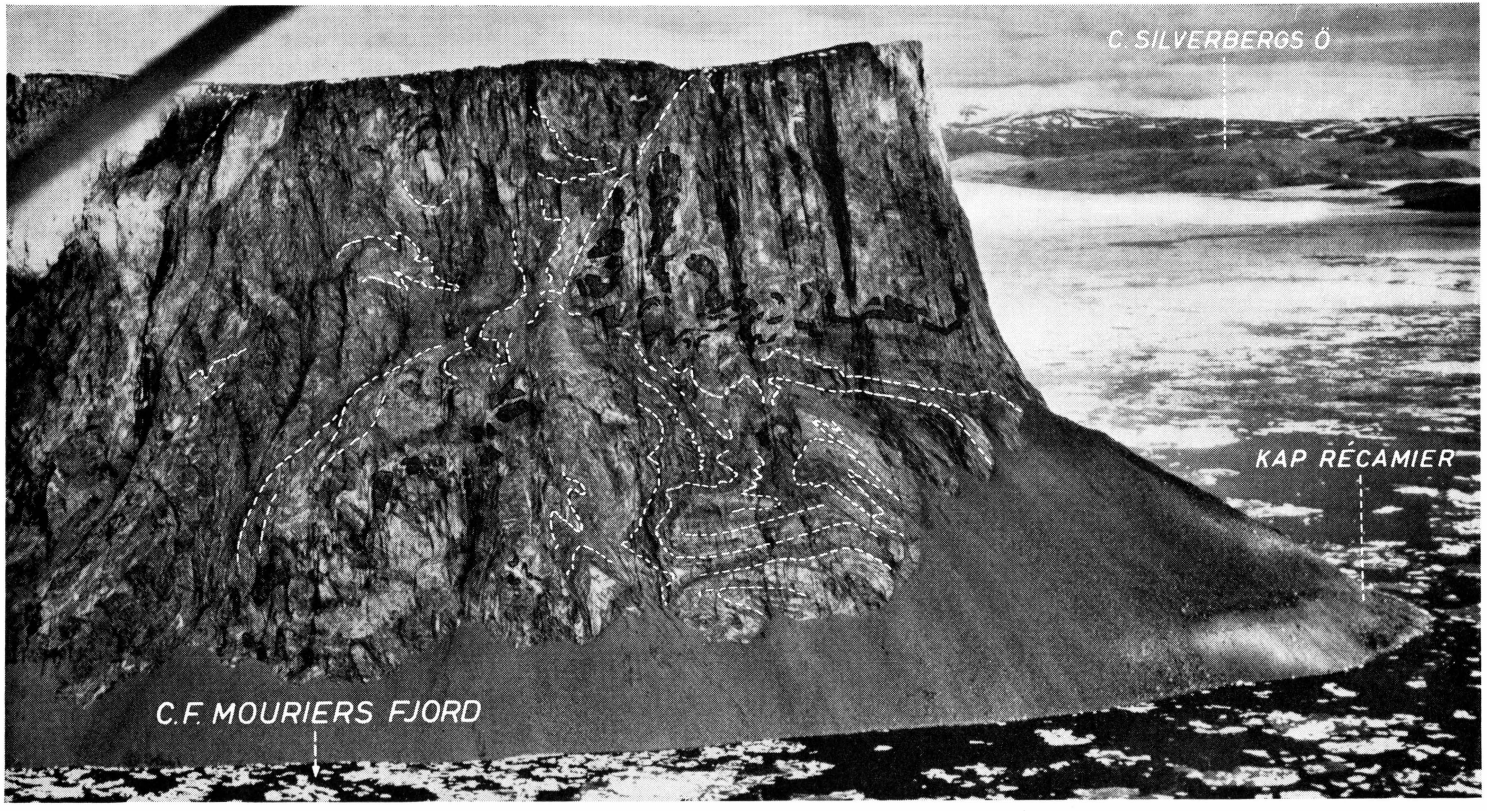


Fig. 37. Caledonian infrastructure in the Skærfjorden area: flow folds underlie and overlie semi-plastically reworked basement blocks. The cliff is some 1,000 m high. — Air-phot. W. DIEHL, 1955.

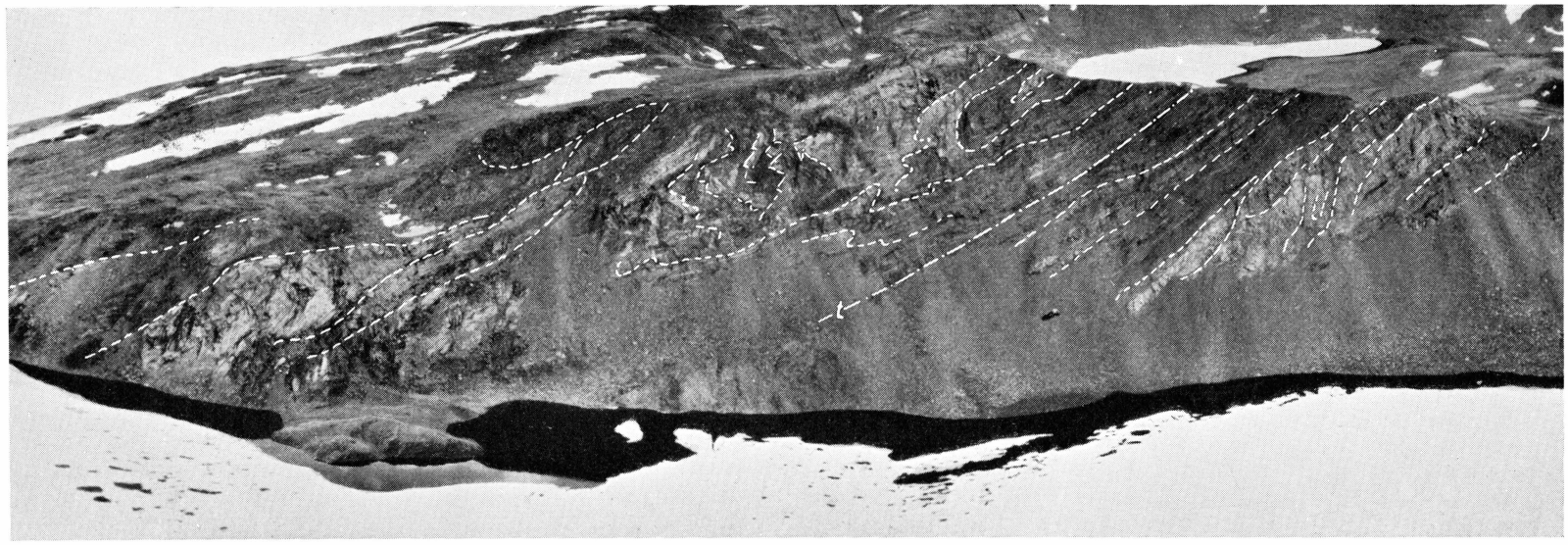


Fig. 38. Alternation of rigid and plastic style of reactivation at the northern periphery of the Skærfjorden complex. Flyversø, Nordmarken (77°50′N). — Air-phot. W. Diehl, 1955 (Photo-montage by Messrs. R. & W. Eidenbenz).

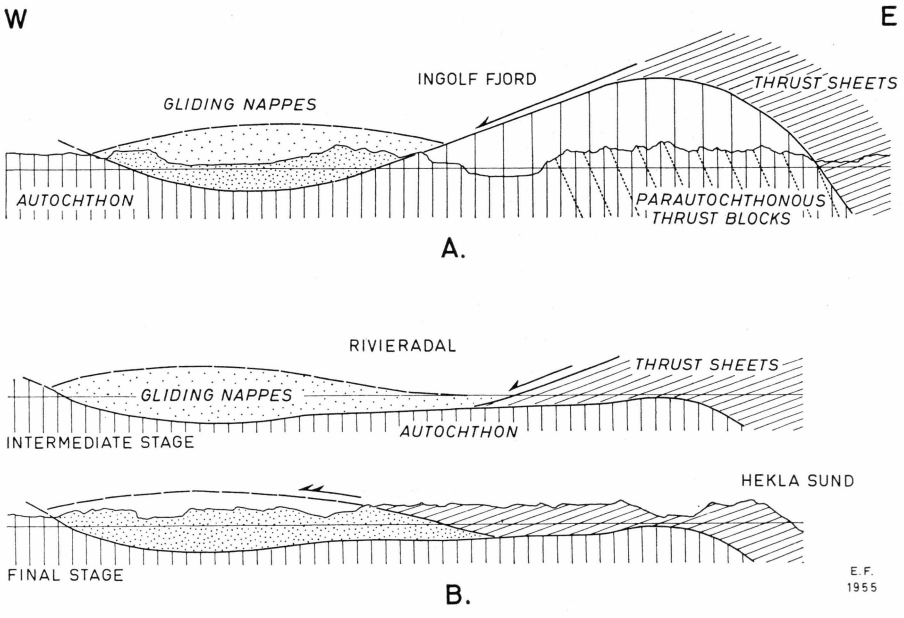


Fig. 39. Structural relationship of passive *gliding units* and active *thrust sheets* in the nappe assemblage of Kronprins Christian Land. In the northern area (section A) the nappe units are supposed to have been emplaced entirely by automotive gliding. In the southern area (section B) the active thrust units moved over the earlier emplaced gliding mass. Modified after E. Fränkl (1955, p. 27).

In Nordmarken, which lies northwest of the Skærfjorden area, the mantle of the rejuvenated complex was found to consist of a linear cluster of Carolinidian gneiss folds, trending NNE–SSW. The Caledonian overprinting affected this belt by coaxial adjustments. Where the front of Caledonian migmatization lies beneath the present exposure level, again an alternating style of rigid and plastic deformation is present (Fig. 38).

From the sequential sections shown on Fig. 31 it becomes obvious that the **thrust and nappe sheets** exposed all along the edge of the Caledonides north of the 76th parallel are part of the superstructure, regardless of the origin of the rock material which makes up the overthrust units.

In Dronning Louise Land and in the nunataks north thereof the Caledonian thrust sheets are made of Carolinidian crystalline series (including pre-Groenlandian basement and weakly to highly altered Thule Group). In Kronprins Christian Land, similar rocks emerge in the rugged 'central chain' forming parautochthonous thrust blocks and

wedges. The allochthonous thrust sheets, however, are entirely made of a post-Carolinidian sequence (Hagen Fjord Group, whereas Paleozoic beds have not been found hithertho in this allochthon). On previous pages it was concluded that these beds represent the filling of a geosynclinal basin ('marginal trough') and reached a thickness of some 5,000 meters. The original position of the trough was presumably somewhere to the east of the present coast area. Hence, the virtual *root zone* of these nappes is not known. The basin filling was squeezed out by Caledonian movements acting towards the west. However, in the course of this process a particular group of beds, that is the 150–200 m thick sequence of alum-shales near the base of the "Taagefjeldene Greywackes" played a decisive rôle in the layout of the present nappe structure. In a mature stage of the formation of the nappes these beds of distinctive lithology provided slip planes for *gliding action*. According to FRÄNKL (1955, pp. 27–29, 33) the presence of these lubricating shales in the moving thrust pile led to a differentiation into *thrust sheets* proper and automotive *gliding nappes*. FRÄNKL (*l.c.*) outlined the structural relationships of these thrust sheets and gliding nappes in a diagram. Part of this is reproduced on Fig. 39 showing schematic cross-sections through the areas adjacent to Ingolf Fjord and Hekla Sund respectively. A more accurate statement on these nappe structures can be obtained from comparing the Tectonic Map with the sets of geological sections published by FRÄNKL (1954, pl. 2; 1955, pl. 2).

B. Late Caledonian Spasms

(Called "young" Caledonian folding, Devonian)

Late orogenic movements and igneous activity are restricted to the territories south of the 76th parallel. The structures formed are manifold in appearance; they also differ in age, probably being spread throughout the whole Devonian epoch. However, only Middle and Upper Devonian events are ascertainable from the stratigraphic record. It is not easy to organize the late Caledonian happenings since different types of earth movements interfere; effects of crustal widening alternate with compressional structures, faulting interacts with folding, and erosion relieves sedimentation. As these processes also overlap in time we are not able to order them chronologically either.

In the early stage of exploring East Greenland's geology, of course, this variety of structural features was puzzling. The orogenic history was obscure. It was especially in the early thirties that this intricate succession of tectonic events, including pre-Middle Devonian structures,

caused much confusion and controversy concerning the *style of Caledonian tectonism* in East Greenland. LAUGE KOCH and his petrographers, BACKLUND and WEGMANN, who postulated a deep going Caledonian orogeny, were mainly faced with the deep-seated mountain structure in the inner branches of the Kejser Franz Josephs Fjord system, that is to say the main Caledonian infrastructure. On the other hand, those who advocated a superficial tectonism—the geologists of J. M. WORDIE's "Cambridge Expeditions"—were more familiar with sections where late Caledonian structures, particularly thrusts and faults, are predominant. With respect to this historical controversy we have to consider the two aspects alike, since the style of deformation developed in the late stage of the orogeny is remarkably different from that of the major event. In general, the main orogenic structures were launched by deep-seated processes under the influence of a heated substratum, whereas the late Caledonian regimes were predominantly superficial in nature.

Yet, even in late orogenic times, deep-seated structures linked with metamorphism and migmatization also occur. These are localized, however, as the backbone of the "Grandjeans Fjord mountain belt" situated around the 75th parallel. This fold belt trending NW–SE represents a large-scale and deep going cross-warping of the Caledonian architecture. The age of this renewed mountain building is not precisely known. However, it is supposed to have preceded the deposition of the oldest Middle Devonian, the "Vilddal Series", which accumulated south of the mountains at Kap Franklin (cf. Pl. XXXVIII). It is remarkable that the new belt was emplaced near the northern edge of the former Central East Greenland geosyncline and, at the same time, that it took up once more the general trend of the Carolinides.

Approximately at the same time the Grandjeans Fjord mountains rose the area of Kejser Franz Josephs Fjord was subjected to extensive *widening* and subsidence. Tension fractures mark the border of this large *basin structure*. In the depression, stretching between 72° and 74° N, more than 7,000 metres of Old Red Sandstone detritus accumulated. Subsidence and deposition were repeatedly interrupted by folding, thrusting, and erosional episodes. The movements acted frequently from east to west, producing belts mainly trending NE–SW. *Faulting* also occurred and several fracture systems predominantly of northerly strike cut across the Old Red Sandstone basin and extended far to the north and south.

Moreover, the entire area south of the 76th parallel was subjected to numerous *intrusions of late orogenic granites*, which were emplaced syn and post-tectonically with respect to the deformation of the invaded rock units. On the Tectonic Map the two features are presented by means of different symbols (see later).

In the large basin where the Old Red Sandstone accumulated, *volcanic activity* is evident at various times throughout the Devonian period. The eruptions overlapped in time and space with the intrusions of palingenic granites. It is not known whether or not there existed a genetic link between the two. But the mere coexistence of palingenetic and magmatic igneous activity in the same area, which at the same time was much disordered by faulting and folding, underlines—though from another point of view—the severe complexity of the late orogenic history in Central East Greenland.

From the foregoing it is evident that the late Caledonian events were varied and complex. In spite of this, one broad pattern can be discerned: South of the 76th parallel, with denudation in progress, the main Caledonian architecture became divided into zones stretching NW–SE. This direction is oblique to the general trend of the old Caledonian mountain chain, but repeats that of the Carolinidian belt. The northwesterly trend was first acquired in the region of Grandjeans Fjord, where mountains started growth in presumably Lower Devonian times. But the new mountains did not rise from the reworked stumps of the Carolinides. They largely grew in the marginal zone situated between the Central East Greenland geosyncline and the Carolinidian swell, that is inside the realm of the former geosyncline. South of the Grandjeans Fjord mountain belt, the Carolinidian trend is reflected once more by several alignments of compound tensional faults, which are closely related to the subsidence of the Old Red Sandstone basin. The large scale pattern of obliquely directed block segments, each several hundred kilometers wide, was differentially affected by young Caledonian spasms. The nature, intensity, and style of deformation were entirely different within these zones, which may be considered as late Caledonian *structural provinces*. An outline of this pattern is shown on Fig. 40. From north to south the following members can be distinguished:

(1) *Northern highlands*, made up of the Grandjeans Fjord mountain belt.
(2) Down-flexed *graben-like tract*, subsequently filled up with continental Devonian deposits.
(3) *Southern highlands*, which remained rather inactive, but into which a series of large granitic batholiths was emplaced while late orogenic movements affected provinces (1) and (2).

On the northern and southern highlands no outcrops of Devonian strata have been found. The absence of such beds does not exclude, of course, the former existence of minor deposits. We have to imagine that Central East Greenland was the site of continental deposition throughout the entire Late Paleozoic and that in Carboniferous and Lower Permian

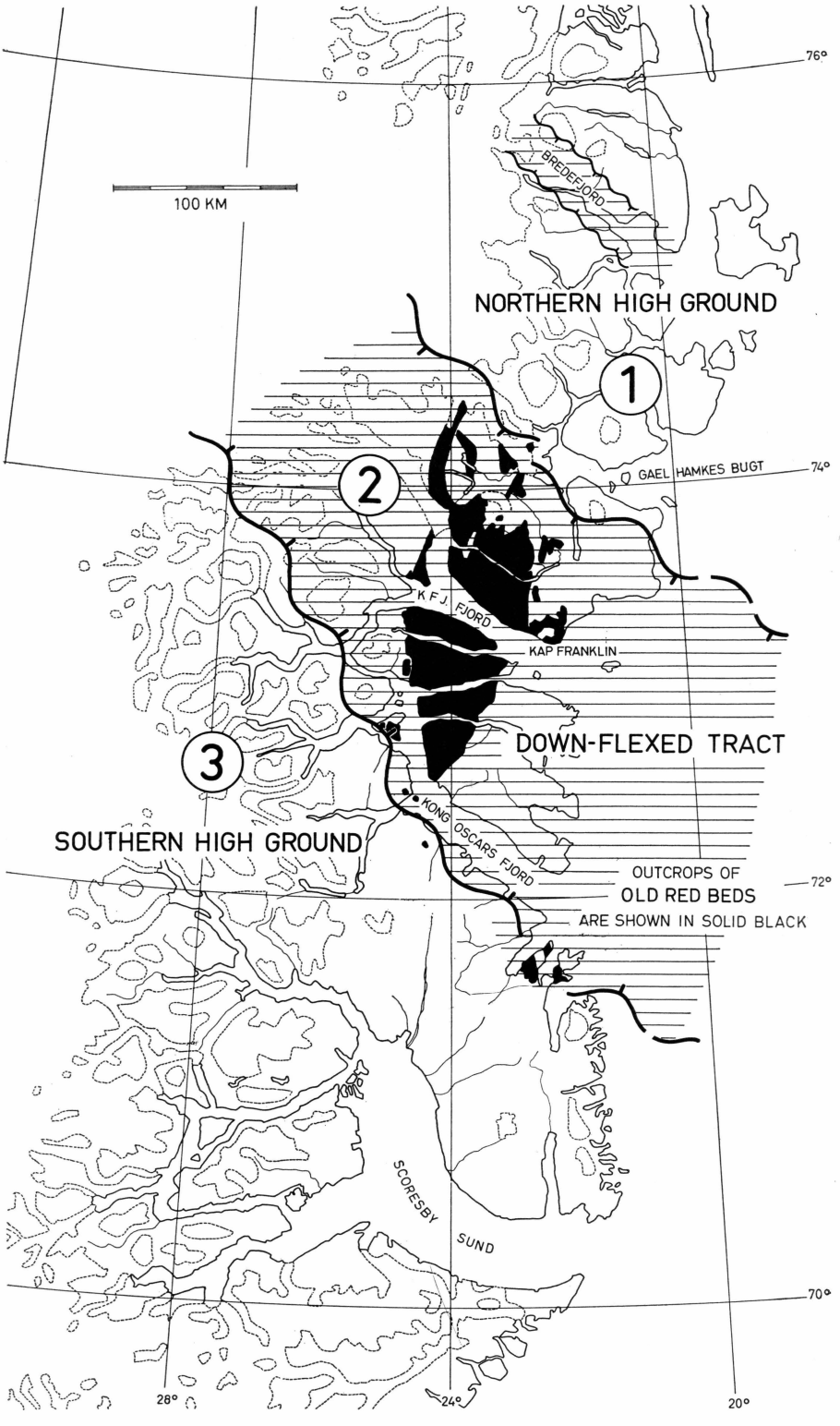


Fig. 40 Late Caledonian structural provinces.

times much rock material was removed by erosion until the mountains were completely planed down. On the Tectonic Map, all *molasse-type sediments* are indicated by light colors, the Devonian by brown, the Carboniferous and Lower Permian by grey shadings.

In the basin province (2), outcrops of *Old Red Sandstone* are widespread, but mainly extend along a north-south zone some 300 km in length (cf. Map 3). Towards the east, the Devonian strata are cut off by Mesozoic to Tertiary faults. Devonian beds certainly continue eastwards on the subsided blocks, which include Carboniferous, Permian as well as Mesozoic sedimentary formations. Although the western limit of the present-day Old Red Sandstone area is largely marked by slopes of the old Caledonian mountains, fault scarps also played an important rôle and attention must be called to these features. Prominent *fracture systems* running N–S succeeded the NW–SE striking low-angle tension structures. The northerly directed fractures were mainly high-angle faults forming step-like arrangements descending eastwards with occasional development of graben-structures.

There is in particular one late orogenic lineament which had much influence upon the layout of subsequent tectonics in provinces (1) and (2), that is an *extensive NNE–SSW fracture* running from Germania Land (77°30′ N) through Dove Bugt, Kong Wilhelm's Land to Nordfjord (74° N). This disruption—called "*Kong Wilhelm's line*"—apparently preceded the pattern of northwest alignments but was repeatedly renewed during the Devonian. The strike of this fundamental line still reflects the major trend of the old Caledonian pattern. Between 76° and 75° N, displacements along the rupture certainly took place prior to the upfolding of the Grandjeans Fjord mountain belt. The spectacular "*Nordfjord graben structure*" was gained by a renewal of the line, south of the 75th parallel, at the turn of the Middle to Upper Devonian. This extensive and long-lived disruption dies out in the Kejser Franz Josephs Fjord area.

The Grandjeans Fjord mountain belt

The Grandjeans Fjord mountain structure traceable between Bessels Fjord and (76° N) and Clavering Ø (74° N) represents the first major spasms of late orogenic activity. The center of tectonism lies evidently in the Grandjeans Fjord region, where infrastructural conditions revived. This particular feature of revived migmatization, indeed, may be causally linked to the Caledonian main orogeny. In the focus Grandjeans Fjord, plastic style refolding even suggests that it represents an after-effect of the heat aggregated by the main orogeny. Yet we have to consider that the old Caledonian complex involved in the Grandjeans Fjord fold pattern underwent faulting as well as erosional truncation

prior to the renewal of orogenic action. Throughout the area discussed the remnants of the old Caledonian fold belt trend northeasterly, both infra- and superstructure running co-axially in the whole area. The superimposed pattern, in turn, everywhere trends northwesterly, thus demonstrating *cross-folding* on a large scale.

I already called attention to the early existence of the fundamental fracture line running NNE–SSW from Germania Land to Nordfjord ("*Kong Wilhelm's line*"). This fracture and its kindred preceded the young mountain building. Similarly, a NW–SE trending graben-structure, some 30 km wide, was formed prior to refolding. It was this early depression, situated around Bredefjord (cf. Fig. 40), that preserved parts of the old Caledonian superstructure consisting of nonmetamorphic Eleonore Bay beds. By the time of the onset of the new mountain building north and south of this depression considerable parts of the old superstructure had already been removed by erosion.

In the northeast, an *en echelon* thrust-system outlines the boundary of the Grandjeans Fjord regime due to forces acting from the infrastructural center (cf. HALLER and KULP, 1962, p. 52). The western edge of the refolded block was apparently controlled by the "Kong Wilhelm's line", that is to say, only in a few places do traces of superimposed folding extend to the west beyond that fundamental fracture. The southern boundary of the refolded tract was distinguished by the imposition of the basin province (2), which evidently acted as the back-trough of the new mountains.

In the area stretching from Smallefjord over Grandjeans to Tyrolerfjord the renewed pattern of the infrastructure rose like a tumor through the older gneiss complex. The folds of the old Caledonian architecture were remobilized and refolding about axes perpendicular to the old. The new deformation occurred in a plastic, mobile environment (Fig. 41). Although young and old fold-axes are seen crossing each other at right angles, there is a definite predominance of the superimposed northwest pattern.

Inside the renewed infrastructure, a few rock masses with steep axial plunge represent the detached remnants of the old complex (Fig. 42). But they are not the only signs of pre-existing structural forms; the shapes of the new folds betray the existence of former folds in the reactivated material. In particular, the major folds seen in inner Grandjeans Fjord show shapes which can only come about by the superposition of two fold systems. There, the same type of fold occurs repeatedly: recumbent folds with the limbs dipping southeast. Plate XXII shows a section running parallel to the young fold axis. The outcrop shown on Fig. 43 cuts obliquely through the superimposed pattern and reveals conspicuous drag-fold structures and contortion inside fold cores (cf.

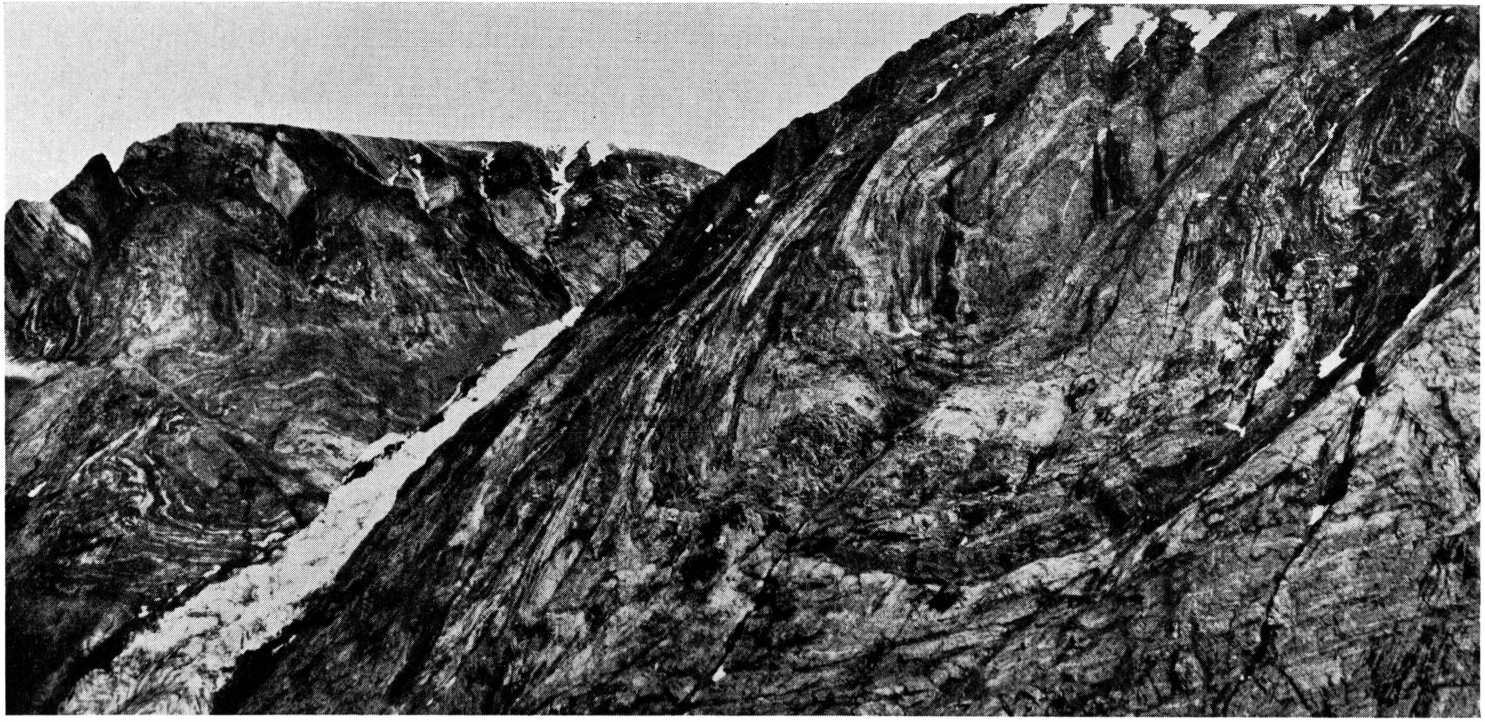


Fig. 41. The renewed pattern of the infrastructure rose in a plastic mobile environment through the older gneiss complex producing refolded folds of homogeneously plastic style. Southern wall of upper Svejstrups Dal (A. P. Olsens Land, 74°40′ N).
Air-phot. F. SCHWARZENBACH, 1956.

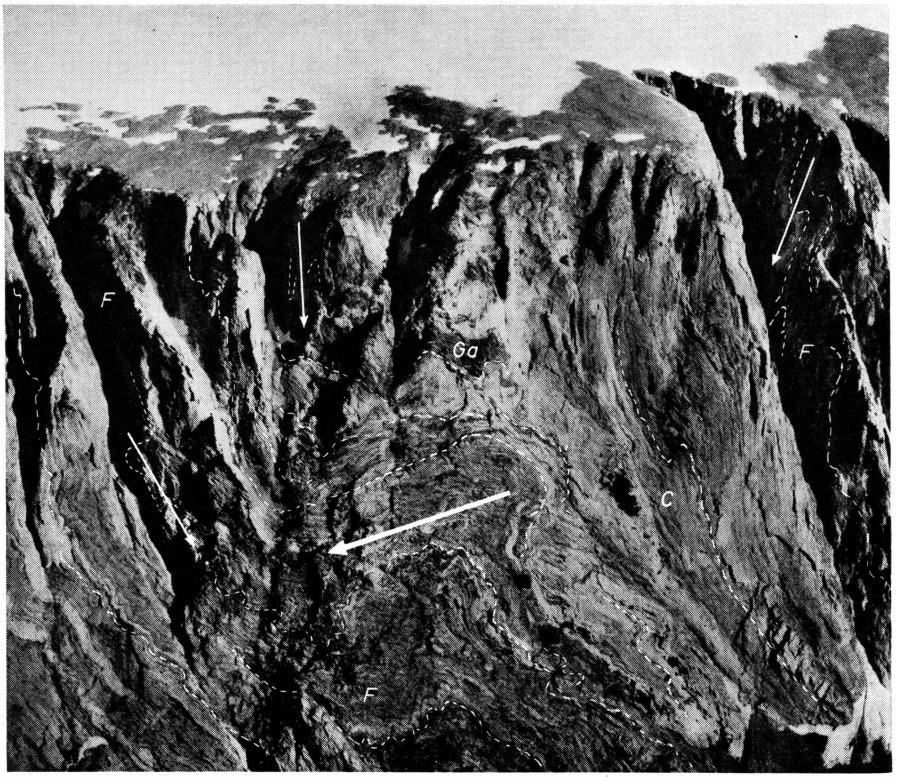


Fig. 42. Inside the renewed infrastructure, detached remnants of the old complex are to be seen with steep axial plunge (thin arrows). The axes of the superimposed pattern are horizontal or plunge gently (thick arrow).

C = leucocratic migmatite-granite, *F* = banded gneiss, *Ga* = amphibolite. Cliff in a side-valley of Birkedalen (Th. Thomsens Land, 75°00′ N). — Air-phot. F. SCHWARZENBACH, 1956.

HALLER, 1957). In the west, the renewed infrastructural zones comes up sharply against a block of old gneisses which remained largely unaffected. There we find similar contact relations as those to be seen around the large masses of Carolinidian gneisses in the Dove Bugt region (cf. pp. 86–90).

It was mentioned that prior to the Grandjeans Fjord spasm parts of the old superstructural mantle were downcast in a graben-like depression, situated around Bredefjord. Moreover, NE–SW striking faults, presumably closely related to the formation of the "*Kong Wilhelm's line*" farther west, dissected the depression transversely. Thus, the young folding about northwest axes, launched by the rise of the renewed infrastructure, affected a mosaic of somewhat cube-shaped fault blocks. The drive of the new tectonics is towards the northeast. This is indicated



Fig. 43. Cliff section, some 500 meters in height, showing drag-fold structures and crumpling in fold cores. This profile corresponds largely to the old Caledonian folding direction in the Grandjeans Fjord interference pattern. Southern wall of innermost Grandjeans Fjord. — Air-phot. F. SCHWARZENBACH, 1956.

by the shape and arrangement of flow folds in the Grandjeans Fjord focus, but becomes even more pronounced in the superstructure. For in the area northeast of Grandjeans Fjord, the older blocks were involved in refolding but first of all in significant thrusting. From the head of Bessels Fjord a belt of heavy thrusts stretches southeasterly. It carries Eleonore Bay sediments over a truncated block of old Caledonian crystalline series.

South of Bessels Fjord, the horizontal displacement of the *overthrust mass* amounts to 5–10 km (Fig. 44). The nappe sheets are entirely made up of mantle portions of the old Caledonian architecture which occupied the former Bredefjord graben area. The block of Old Caledonian crystalline rocks in front of the nappe structures, in turn, is sliced up



Fig. 44. South of Bessels Fjord, a thrust-system outlines the edge of the Grandjeans Fjord fold belt. Nappe sheets of nonmetamorphic Lower Eleonore Bay beds (*4*) were carried over a truncated complex of old Caledonian migmatite-granites (*C*), banded gneisses (*F*), and mica-schists (*J*). The dash-dot lines (*t*) indicate the base of the overthrust mass. The emplacement of the nappe arrangement was partly accompanied by syn-tectonic granite intrusions (*N*); major intrusions, however, occurred in the form of post-tectonic (*O*) stocks and batholiths, one of which is seen at Knæksø. (*f*) indicates a later fault. — Air-phot. W. Diehl, 1958.

by various sets of thrust and shear planes striking roughly parallel to the major overthrust. However, not much displacement can be related to these thrust slices and hence they are considered to be parautochthonous. Some low-angle thrust faults on the southern Store Koldewey Ø are also thought to be related to these structures. *Tear faulting*[54]) is another salient feature in the layout of this superstructure. The earlier NE–SW fault pattern outlined the scars which now yielded slip planes for differential folding and horizontal displacement of adjacent fault blocks. A major flaw occurred along the northwestern edge of the refolded area, that is along the "*Kong Wilhelm's line*" at its type-locality (*i.e.* Kong Wilhelm's Land).

Old Red Sandstone sedimentation

The Devonian accumulations of East Greenland have been compared by various authors with the Alpine *molasse*. Such a comparison is based on great similarities to the latter with respect to thickness, type of sediments and mode of formation, together with the style of folding and up-thrusting caused by late orogenic movements. In other features, however, no similarity can be found. Above all there are great differences as to the relation in time and space to the corresponding mountain structure. The East Greenland Old Red Sandstone accumulated in an *intramontane basin area*, designated province (2) on previous pages. Thus it must be called "*intramontane molasse*" ("Innenmolasse", according to S. VON BUBNOFF's classification). Also the East Greenland formation was formed at a relatively later stage of peneplanation than the Alpine molasse. Much volcanic material, in the form of lava-flows, tuffs and tuffites, is mixed with the Old Red Sandstone at many places. No marine deposits are known so far. However, all principal groups of lower fossil vertebrates are represented, indicating *Middle* and *Upper Devonian* ages. The East Greenland Old Red Sandstone is well known as the only locality to yield *Ichthyostega* sp., a four legged fish, which is the oldest and most primitive tetrapod.

The molasse basin includes more than 7,000 metres of red beds (see Plate XLIV, Section A–A′). The Middle Devonian basal deposits overstep strata involved in main Caledonian folding by nearly 8,000 meters, which means that the Old Red Sandstone was poured upon a deeply eroded mountain complex. Due to this environment – interior lands of a fold belt which was still active to a limited extent—these

[54]) "*Tear faulting*" refers to strike-slip displacement that appears to tear fold structures across, that is to say, the folds in one block are more tightly compressed and closely spaced than in another. Thus, the term '*tear fault*' denotes strike-slip displacement that originated during the folding though, as a rule, this type of faulting represents a re-juvenation of pre-existing fractures.

molasse beds reacted quickly to regional and local stress. All dislocations affecting the substratum were transmitted to the land surface as well. Thus depositional environments changed rapidly with the development of new swells and secondary basins. The composition of the clastics changed as the boundaries of the supply area shifted. Already formed strata were in places involved in the dislocations; they were bent or fractured, and sometimes also removed by erosion. The rocks of the pavement were pushed up, broke through the roof of molasse beds and rose into the air. In these uplifted and upthrust belts erosion unloading quickly set in, and in the adjacent troughs younger molasse series transgressed across the older ones. Hence, profound disconformities can be determined and from this different cycles of Old Red Sandstone accumulation can be traced (cf. Map 3). H. BÜTLER called these tectono-environmental units 'orogenic series' and distinguished them as follows:

"Mount Celsius Series" "Kap Graah Series"	Upper Devonian
"Kap Kolthoff Series"	Upper Devonian and/or Upper Middle Devonian
"Ramsay Bjerg Series" "Basal Series"	Middle Devonian

An accurate subdivision of such 'orogenic series' is only possible where clear unconformities occur, that is, at the margins of the trough. However, one can follow them further with some certainty where the basal conglomerate of the unit can be recognized by its specific pebble content.

The delimitation of these series was made in the area around *Moskusoksefjord* where they are separated from one another by well-exposed angular unconformities, and where there is a stratigraphic gap between any two series (cf. H. BÜTLER, 1959). On the Tectonic Map, however, all pre-Kap Kolthoff formations have been collected under the term "basal sequences".

On the map, the area of Devonian rocks forms an intermediate block about 60 km broad and 150 km long between the uplifted inner fjord zone and the sunken tilted outer coast blocks. In the center of this block, the Old Red Sandstone reached its maximum thickness. Here the beds follow each other rather concordantly and conglomeratic intercalations are insignificant. Along the western margin of this area, Middle Devonian *basal conglomerates* are widely distributed, resting mainly on Eleonore Bay beds, the Tillite Group, or on Cambro-Ordovician strata (Plate XXIII). The coarse clastic features of the "Basal Series" and its

pebble content indicate that the present western margin of outcrops coincides with the former western edge of the depositional area of the lowermost Old Red Sandstone. At that time, there was an uplifted range to the west, with a deepening trough to the east. However, the younger molasse series must have extended farther westwards. Hence the present western limit of Devonian outcrops represents the original trough margin for the "basal sequences" and merely an erosional boundary for the younger series. Scattered intra-Devonian faults and thrust-faults, of a general northerly strike were also among the factors controlling the present western boundary.

On the east side, the Devonian area is cut off by a continuous and topographically prominent fault line. The downthrow is to the east and the Devonian on the deeper block is covered by younger formations. Between Kong Oscars Fjord and Kejser Franz Josephs Fjord, this "*post-Devonian main fault*" runs obliquely, *i.e.* northeasterly, across the meridional arrangements in the molasse trough. North of Kejser Franz Josephs Fjord, the fault joins a northerly running grabenstructure ("*Gastisdal-graben*"), and on the upthrown block east of this line lower Old Red Sandstone series (Middle Devonian) occur around Kap Franklin and also farther north.

Various isolated occurrences of Old Red Sandstone lie outside this main outcrop area. In the north, in Hudson Land and Ole Römers Land, narrow and deeply sunken graben structures as well as tightly squeezed synclines of molasse beds stretch far into distorted blocks of the Caledonian architecture (see later). In the very south (off the area covered by Map 3), further outcrops of Devonian molasse occur at Wegener Halvø and Canning Land (71°35′ N).

Intrusions of late-orogenic granites

There are many intrusive bodies of potash-dominant granites south of the 76th parallel ('diapirites', according to H. G. BACKLUND). Their composition and general appearance suggest a close relationship to the setting of the main orogenic infrastructure. The actual source areas of these 'diapirites' are not seen at the present exposure level. This means that the granites rose from compartments more deeply seated than the infrastructural tier. The 'diapiritic' material evidently became active at the time when the infrastructure had already congealed. Most of the piercement granites were even emplaced after the regional metamorphism, which generally outlasted the process of infrastructural doming. They originated at great depth where migmatization resulted in a thorough melting of the reworked crustal segment, *i.e.* from compartments subjected to *palingenesis*. This happened at a depth of burial of approxi-

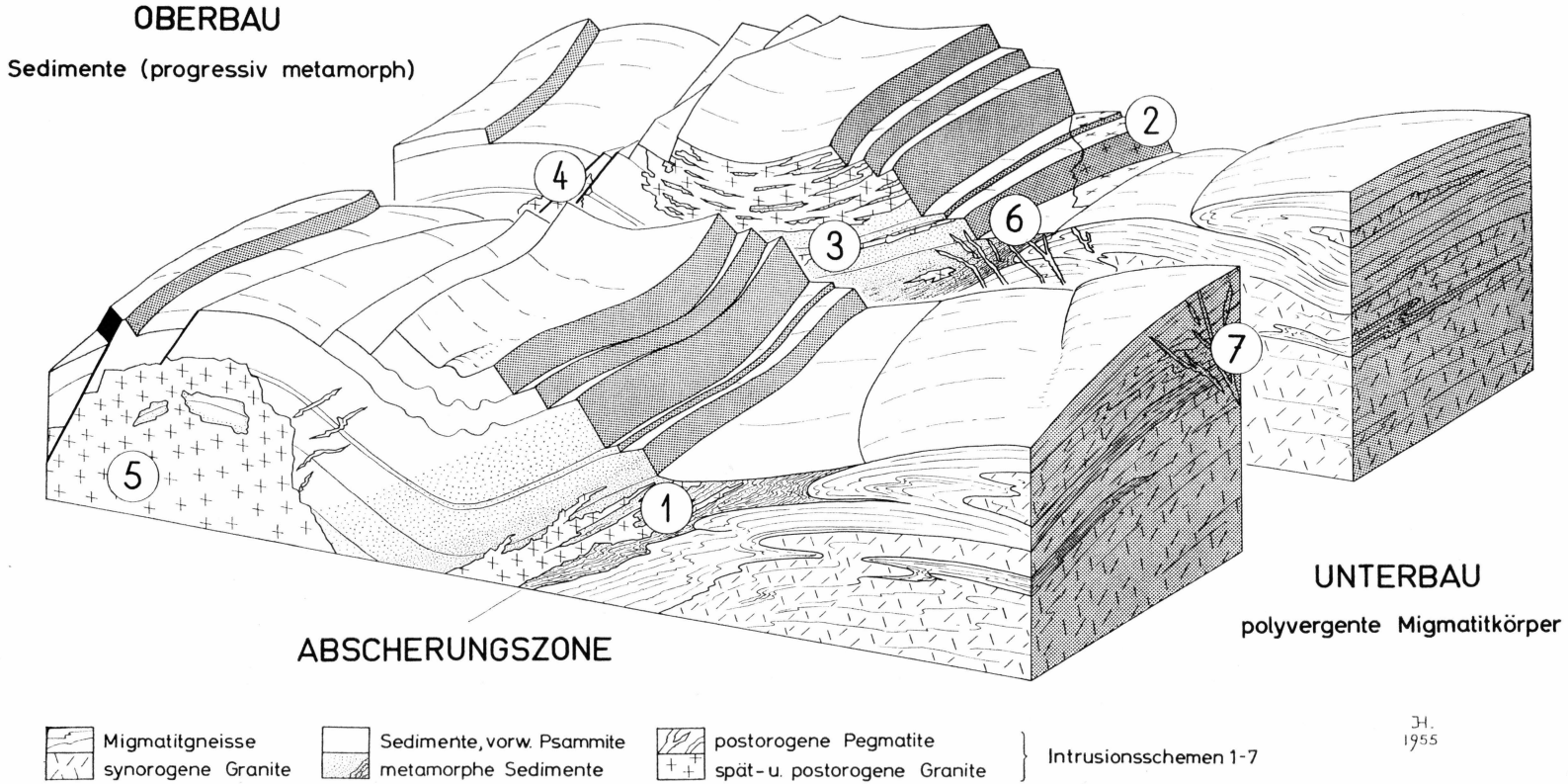


Fig. 45. Diagram showing common types of late orogenic granite intrusions.

mately 15–20 kilometres, a crustal level which might correspond to what is called the 'Conrad discontinuity' found underneath some of the younger fold belts. In late orogenic times, the reborn granitic molten fluid ('migma-magma') freed itself from its plutonic associates and moved high in the crust, even into non-metamorphic regions, to appear there as intrusive cross-cutting granites with a constant composition over the whole area. From the genetic point of view these 'diapirites' are '*palingenites*'.

It is remarkable, however, that the intrusions did not break through centers of infrastructural doming, but followed the periphery of greater infrastructural bodies. They mainly settled into the domain of disharmonic detachment between infrastructure and superstructure, that is to say they are mainly situated along zones of weakness left in the main Caledonian architecture. Other intrusions were guided by fracture lines or thrust systems. The granites are mainly post-tectonic with respect to the deformation of the invaded rock unit, but some granites evidently crept into place while movement preceded. In cases of such syntectonic emplacement there is an intimate connection between folding, thrusting, and the intrusion of granitic melt.

1) Post-tectonic intrusions.

Some common types of post-tectonic granite intrusions are shown schematically in Fig. 45. As mentioned above various granite bodies settled in the form of sheets or smaller stocks into the zone of detachment as did *types 1* and *2* on the scheme. Examples of this mode of emplacement are portrayed on Figs. 46 and 47. *Type 3* refers to complex sheet intrusions which generally were emplaced by lateral injection often following the keel of an open syncline of the Caledonian superstructure (Plate XXIV). *Type 4* shows an intrusion which was guided by low-angle faults, mainly tension fracture systems. The granite crept into space that was opened by means of tensional tectonics. The room was more or less passively occupied by the intruding material. An impressive example of this type is to be found in Scoresby Land (72°15′ N), at the north-eastern flank of the Staunings Alper massif[55]). *Type 5* represents one of the smaller batholiths whose age of emplacement can often be dated relative to adjacent fault lines. This type of granite body settled mainly into the broadly folded sedimentary pile of the superstructure, preferably into anticlinal structures. It is interesting to note, that these massive and homogeneous granite batholiths did not reach horizons stratigraphically higher than the Quartzite Series, which means that at the time of emplacement these plutons were buried some 4,000 to 5,000 metres.

[55]) Cf. J. HALLER (1958, pp. 128–36, pl. 12).

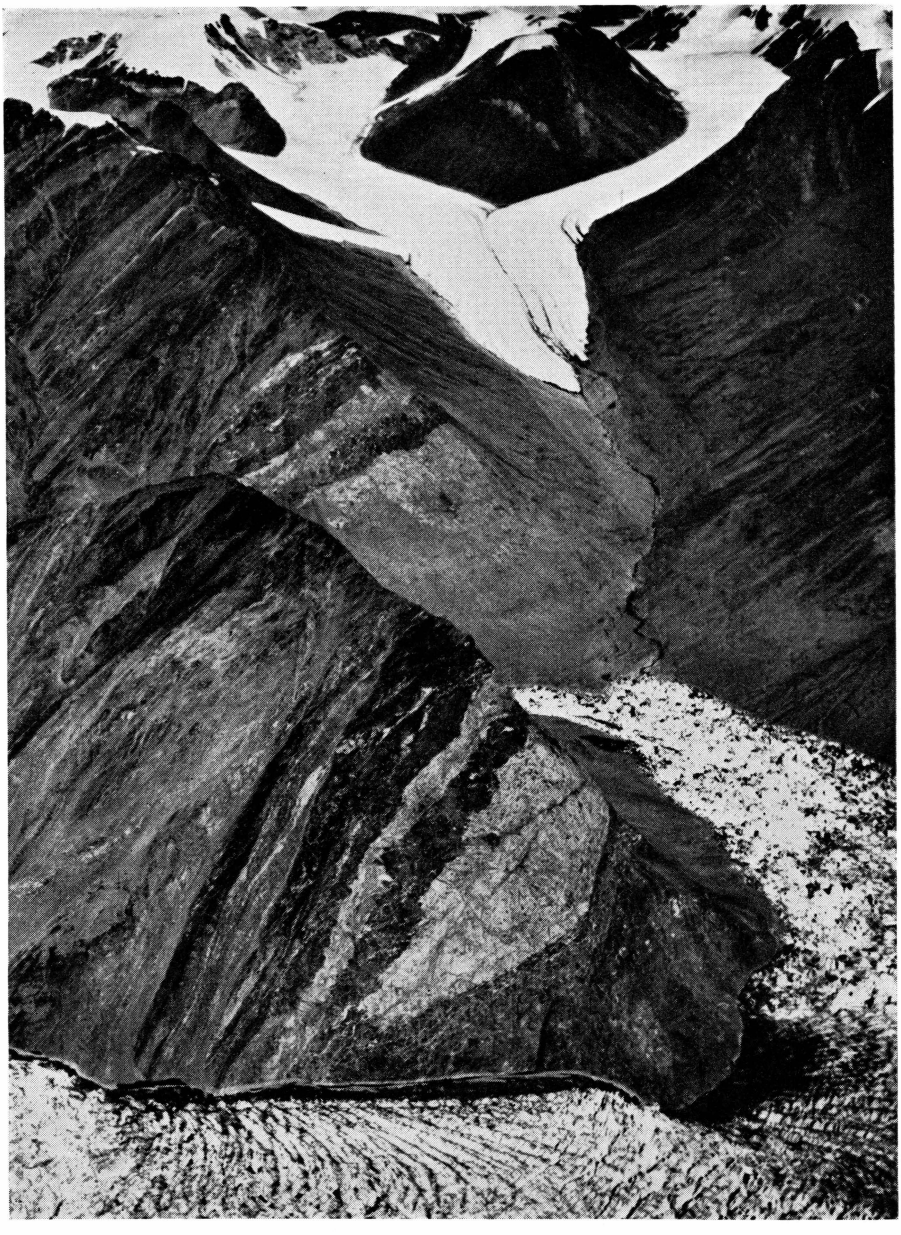


Fig. 46. Sphenolithic sheet of intrusive granite at lower Jættegletscher (Louise A. Boyds Land, 73°27′ N). — Air-phot. E. HOFER, 1951.

Along the batholiths' margin as well as in the wall of country rocks, marks of forcible intrusion, magmatic stoping, and block foundering are clearly and frequently displayed. An example of this type of batholith, some 10 km in length, is shown om Plate XLIII portraying the

Fig. 47. Sphenolithic, step-like sheet of intrusive granite, Indelukket (Bartholins Land, 74°20′ N). — Air-phot. F. SCHWARZENBACH, 1956.

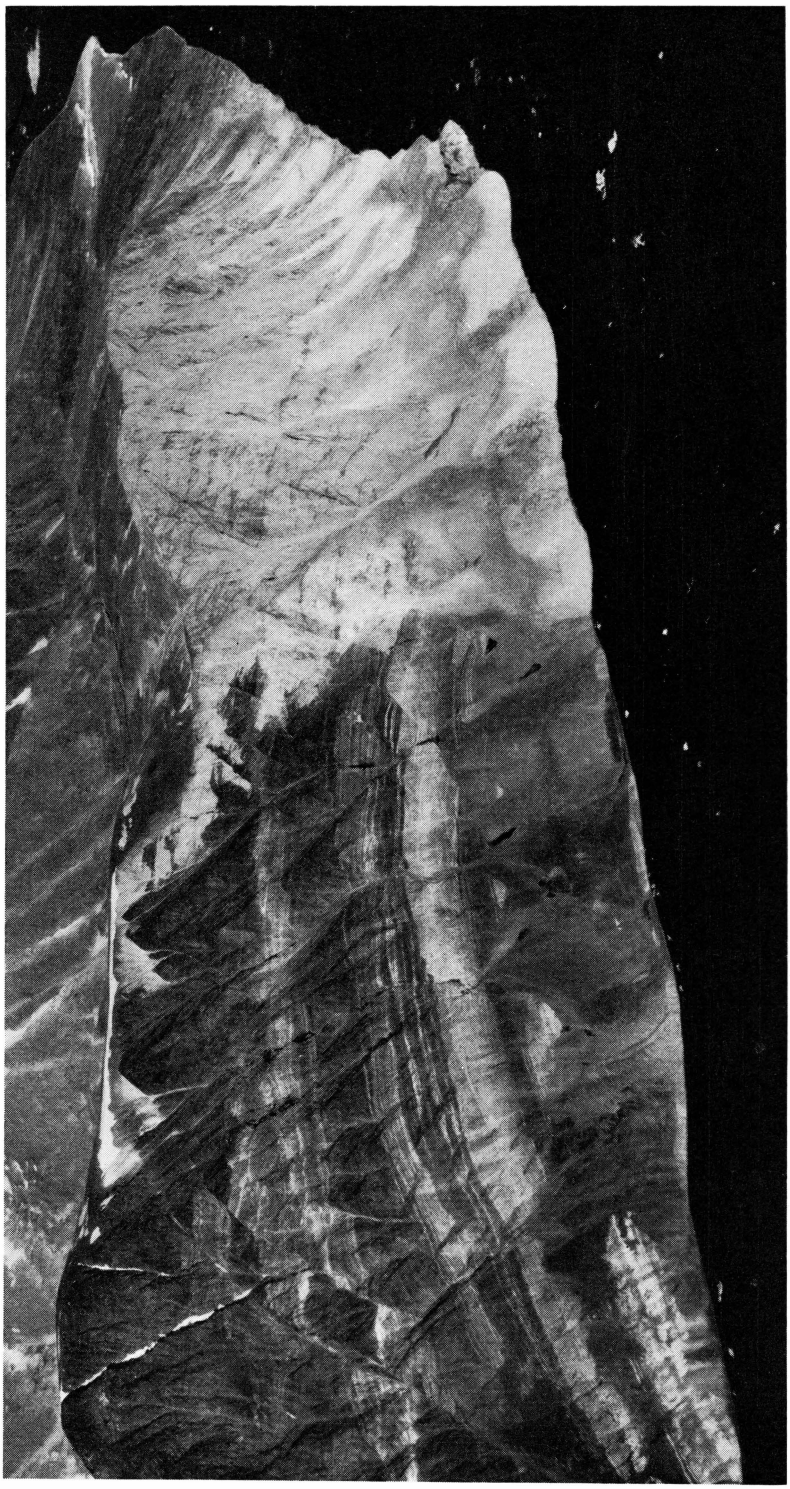


Fig. 48. Post-tectonic granite pluton at Kap Klinkerfues (Ardencaple Fjord, 75°20′ N). The intrusion cuts through well stratified quartzites and quartzitic schists of the Lower Eleonore Bay Group. Post-granite faults are seen to the left. — Air-phot. W. Diehl, 1958.



Fig. 49. Sheets of syntectonic intrusive granite (*N*) squeezed into a recumbent flow fold structure. The twisted lamellae detached along a rather sharply defined zone (*d*) from the stiff and relatively less moved wall, consisting of leucocratic gneisses (*F*) and mica-schists (*J*). This outcrop and its rightward extension shown on Figure 50 is part of a WSW-ENE stretching mobile belt in northernmost Andrées Land (74°00′ N). — Air-phots. F. SCHWARZENBACH, 1956.

pyramidal to cupola-shaped Grejsdalen pluton (Andrées Land, 73°35′ N). Another intrusive body of the same size order which has vertical to funnel-shaped side walls but is not so well-formed as the Grejsdalen pluton is shown on Fig. 48 from Kap Klinkerfues (Ardencaple Fjord, 75°20′ N).

It was earlier mentioned, that in late Caledonian times the southern highlands, *i.e.* structural province (3), remained rather inactive while movements related to molasse sedimentation affected the provinces (1) and (2). Yet in the southern tract consisting mainly of segments of the old Caledonian infrastructure a series of *large granite batholiths* was



Fig. 50.

emplaced. Map 3, however, covers only part of the area concerned. The intrusions are placed on two lineaments striking north-northeasterly: the batholith in *Charcot Land* (72° N) has a longitudinal axis of some 40 km and the narrow complex sheet pluton at *Nordenskiölds Gletscher* (73° N) a longitudinal axis of some 60 km. These two major plutons set the first alingment. The second one runs parallel but lies some 120 km to the east, consisting of a fairly continuous area of batholithic invasion stretching from the *Staunings Alper massif* (72° N) to *Renland* (71° N).

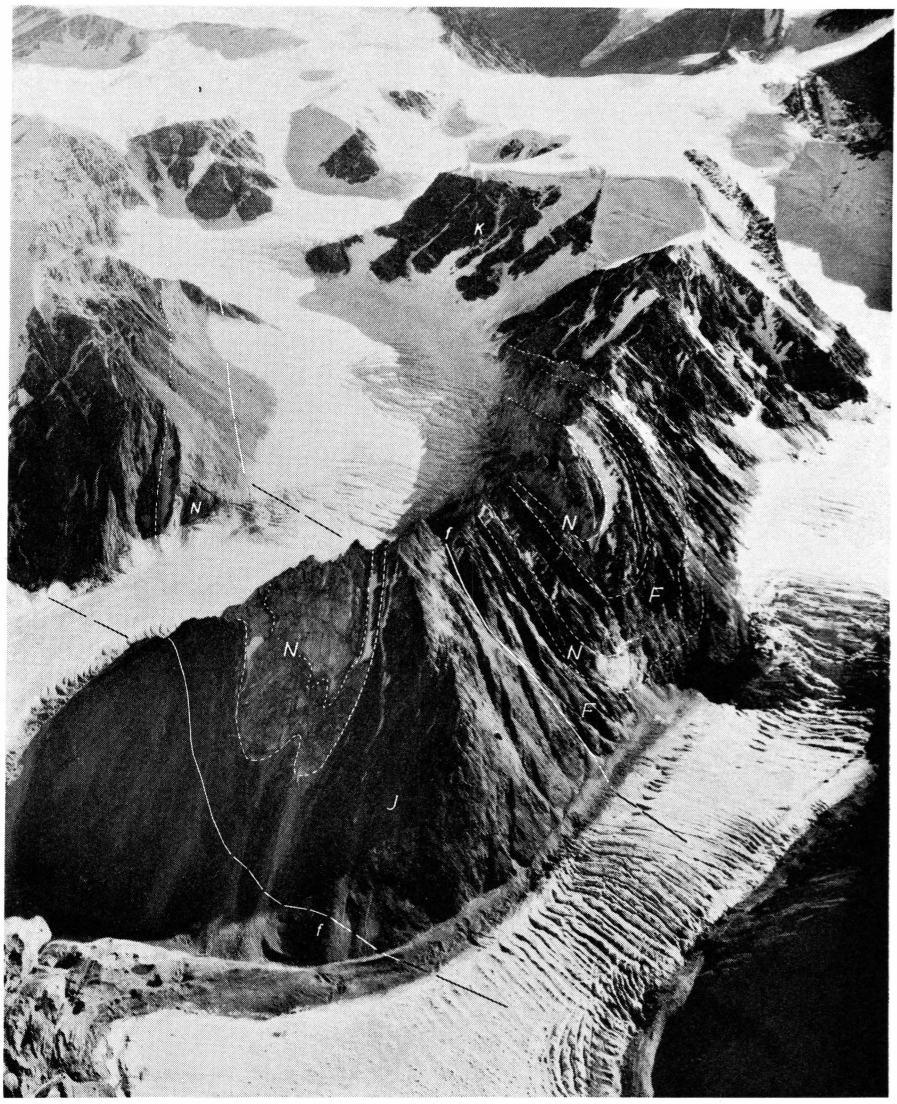


Fig. 51. Lamellae of plastically folded syntectonic intrusive granite (N), part of the young Caledonian mobile belt stretching NW-SE across inner Eremitdal (northern Andrées Land, 73°45′ N). *K* = bedded quartzite to gneiss, *F* = banded gneiss, *J* = mica-schists, *f* = faults. — Geodætisk Institut, Eneret Nr. 631-SØ/11,843.

2) **Syntectonic intrusions.**

On the legend of the Tectonic Map of East Greenland, the young Caledonian structural features are subdivided into superficial and deep-seated tectonics. In the realm of the Grandjeans Fjord mountain belt (that is the area north and northeast of Wordies Gletscher which is for

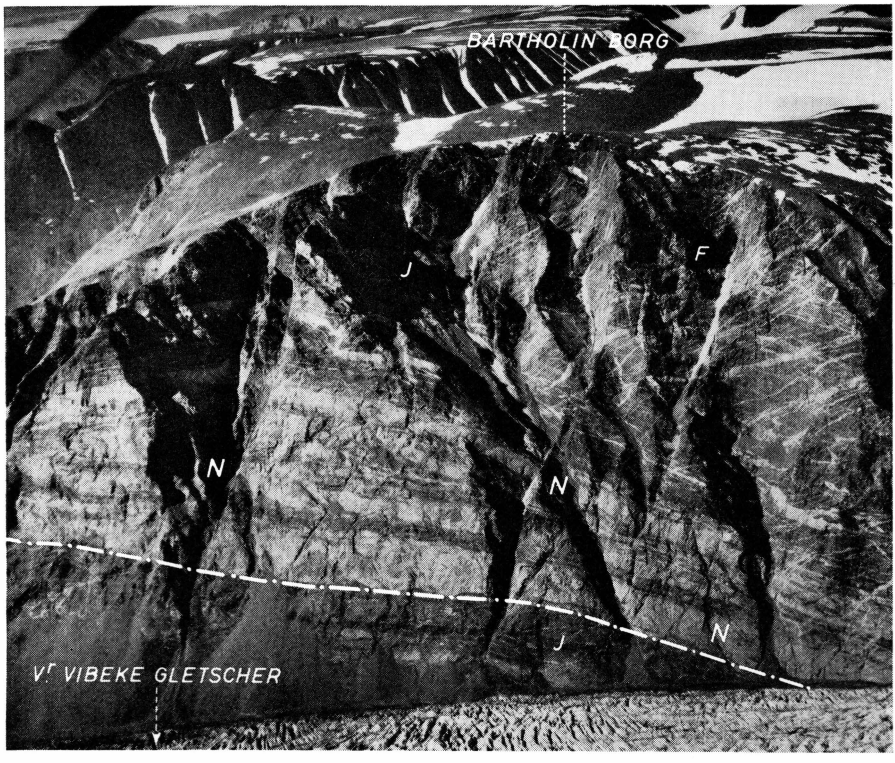


Fig. 52. Syntectonic sheets of intrusive granite (*N*) acting as lubricator on a young Caledonian thrust system. The sole of the thrust zone is indicated by a dash-dot line. The country rocks displaced along these low-angle faults are made up of leucocratic gneisses (*F*), amphibolites and mica-schists (*J*). Bartholins Land (74°25′N). Air-phot. F. SCHWARZENBACH, 1956.

the most part shown on Map 2) all structures referred to as "deep-seated" represent plastic style folds in the revived migmatite "stockwerk" of the new belt. These structures, indeed, are comparable to those of the old Caledonian infrastructure.

In the northwestern quadrangle of Map 3, in the area north of inner Kejser Franz Josephs Fjord, symbols signifying "deep-seated" have been applied to plutonic fold elements brought about by intrusive granite injected simultaneously with the folding process. This peculiar type of plutono-tectonics, however, is confined to fairly narrow but extensive belts. Over large sections there is a close interaction between folding, overthrusting and intrusion of melt. The granites were more or less conformably intercalated between mechanically competent rock complexes. Although there is a great variety among these intrusive systems, two principal types were repeatedly encountered:

(i) Loops of *plastically folded intrusive sheets*, squeezed along narrow belts of intense folding. The adjacent areas in front and back of these

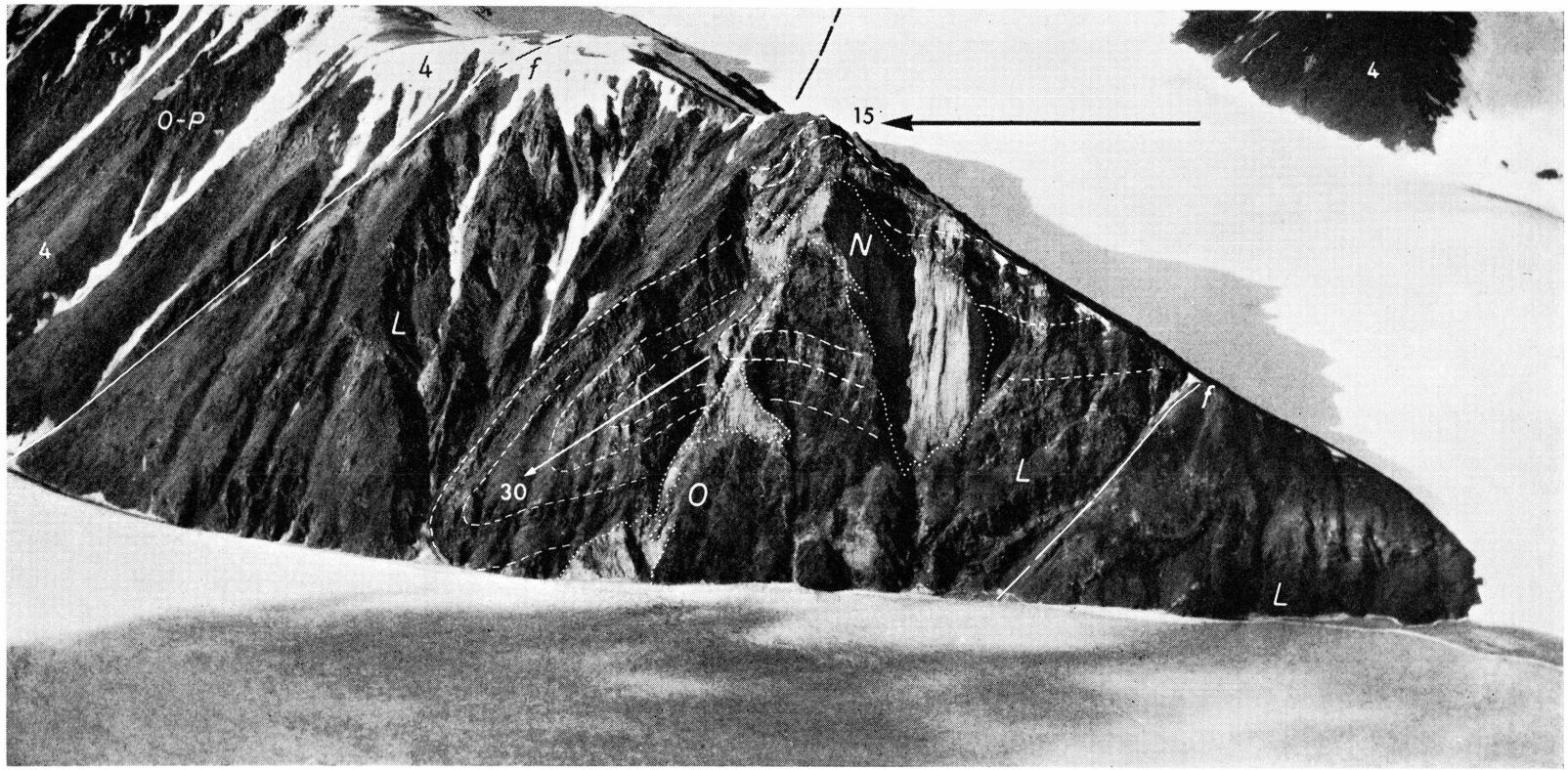


Fig. 53. Tight recumbent fold of the old Caledonian architecture showing an axial plunge of 30° towards south-southwest. The present attitude of this structure was brought about by young Caledonian refolding about an axis plunging 15° towards southwest. A mass of intrusive granite (*N*) clearly penetrates the old structure but is intimately involved in the process of re-folding and thus syntectonic with respect to the younger deformation. (For explanation of symbols see Plate XLVI). North Andrées Land (73°55′ N). — Air-phot. F. Schwarzenbach, 1956.

zones of mobility remained passive and relatively unaffected by the young movements. The injected granite, capable of flow, yielded highly plastic folding while the adjacent areas acted as stubborn blocks. This, of course, caused disharmonic structures and various forms of detachment features producing shears, thrusts and lags (Figs. 49–51, Plate XXV).

(ii) Sheets of diapiritic *granite injected into thrust systems.* The intruded highly viscous crystal mush acted as a lubricator and thus furthered the internal mobility of the growing thrust-fold belts. This type of syntectonic granite emplacement is particularly well developed in the area of Bartholins Land (Fig. 52, Plates XXVI, XXVII).

A peculiar syntectonic intrusive system different from the two types mentioned above is pictured in Fig. 53 showing a nameless nunatak south of Sneharefjeld in northern Andrées Land. This outcrop displays a large-scale refolded fold where granite was emplaced largely simultaneously with the younger deformation.

It should be added, however, that the mineral composition of these syntectonic off-shoots resembles closely that of the ubiquitous posttectonic palingenite intrusions. Yet the syntectonically emplaced granites often show mechanical destruction of their early formed plagioclase crystals. The bulk of the rock fabric, however, was built after the movement ceased.

Tectonics of the intramontane Old Red Sandstone basin and its vicinity

(Entirely shown on Map 3)

After the main Caledonian fold belt was formed and finally rose to mountainous heights, a *period of tension* began in the region of Kejser Franz Josephs Fjord. This crustal widening caused the subsidence of the transverse basin tract, which caught the Old Red Sandstone detritus (structural province 2, cf. Fig. 40). The northeastern edge of the subsided area coincides with the course of Wordies Gletscher; the southwestern edge runs from western Andrées Land to Kong Oscars Fjord. The bordering zones both running NW–SE include extensive belts of flexures and tensional structures, mainly low-angle faults (Plate XXVIII). On the Tectonic Map, this type of fault is generally shown by dash-dot lines, without further indication of its age. The lateral expansion caused by these *early Devonian tension faults* was considerable in part. For example, in northern Scoresby Land (72°20′ N) the cumulative displacement of the fault system has been calculated over a distance of 42 km and the original length of that section was found to be 31 km (E. Fränkl,

1953b, p. 50). In this area, thus the amount of widening is much greater than that of shortening reflected by old Caledonian superstructural folds.

During the deposition of the Old Red Sandstone another pattern of *normal faults* developed. These structures, largely running N–S, caused step-like fault block arrangements and graben structures.

Over the whole basin province and its western vicinity, a number of combined *fold and thrust belts* grew. Yet only in Hudson Land (73°30′ to 74°00′ N) was it possible to restore an incontestable sequence of tectonic events on the basis of breaks in the stratigraphic record. There, *two Middle Devonian* (Hudson Land Phases I, II) and *two Upper Devonian spasms* (Hudson Land Phases III, IV) have been ascertained by H. BÜTLER (1940, 1957, 1959).

As to the entire province two principal movement patterns are discernible, and it was found that the north-northwesterly system was apparently in action before the one with an east-northeast strike. However, repeated movements on both systems may well overlap in time and are likely to be of Middle and Upper Devonian age in either case. Both systems bear features of thrust and fold tectonics partly initiated by syntectonic off-shoots of granite melts. The mutual relation of structures indicate a rise of several generations of granite, all launched by forceful upward projection of molten material that was squeezed out from the sub-migmatitic abyss.

1) **Folds and thrust running north-northwesterly to northerly.**

Due to selective mobility along the southwestern marginal zone of the subsiding basin province (2) a belt of disconnected fold complexes, upthrusts and overthrusts was superimposed on the old Caledonian structures. This superposition apparently represents the initial pattern if intra-Devonian fold belts in the realm of the molasse basin. In North Andrées Land and Louise A. Boyds Land, sheets of intrusive granite (cf. Fig. 51, Plate XXV) are conformably and plastically involved in this folding, which crosses the old Caledonian major structures at an acute angle. The front of the superimposed fold belt is a system of southwesterly directed thrusts (Fig. 54, Plate XXIX). South of Kejser Franz Josephs Fjord, the axes of refolding run co-axially to those of the Old Caledonian superstructure, the open folds of which were then accentuated, tightened, and partly even overturned towards west (Plates XXX, XXXI, XXXII). On Ella Ø, the accentuation of the major anticline can be dated Middle Devonian on the basis of Old Red Sandstone beds involved (Fig. 55).

Notable *strike-slip displacement* caused by their superimposed stress, arose along various pre-Middle Devonian fault systems with differential folding in each fault block. This is particularly well seen at Narhval-



Fig. 54. Late Caledonian thrusts (*t*) and faults (*f*) in northwestern Andrées Land (73°35′ N). *H* = marbles and calcareous schists, *J* = mica-schists to gneisses, *L* = quartzitic schists, *K* = bedded quartzites, *N–O* = syn to post-tectonic intrusive granites, *P* = pegmatites. 5,6 = Lower and Upper Quartzite Series respectively. — Air-phot. E. Hofer, 1950.

sund, where a prominent northwesterly trending fault separates the entirely different architecture of Ella Ø from that of Lyells Land. Another example of a westerly running fault system differentially affected by this folding is revealed by the "Morænadal graben" (western Andrées Land, 73°45′ N).

Another belt of northwest trend but with mere plutono-tectonic features appears in southern Bartholins Land, which is in the interior of the basin tract. There, a granite batholith some 30 km in length was emplaced largely conformably to a couple of open folds, which represent resurgent structures along a former flexure line (Fig. 56).

During the same period of deformation that caused folding and thrusting farther south, thrust-wedges were shoved upward by lateral

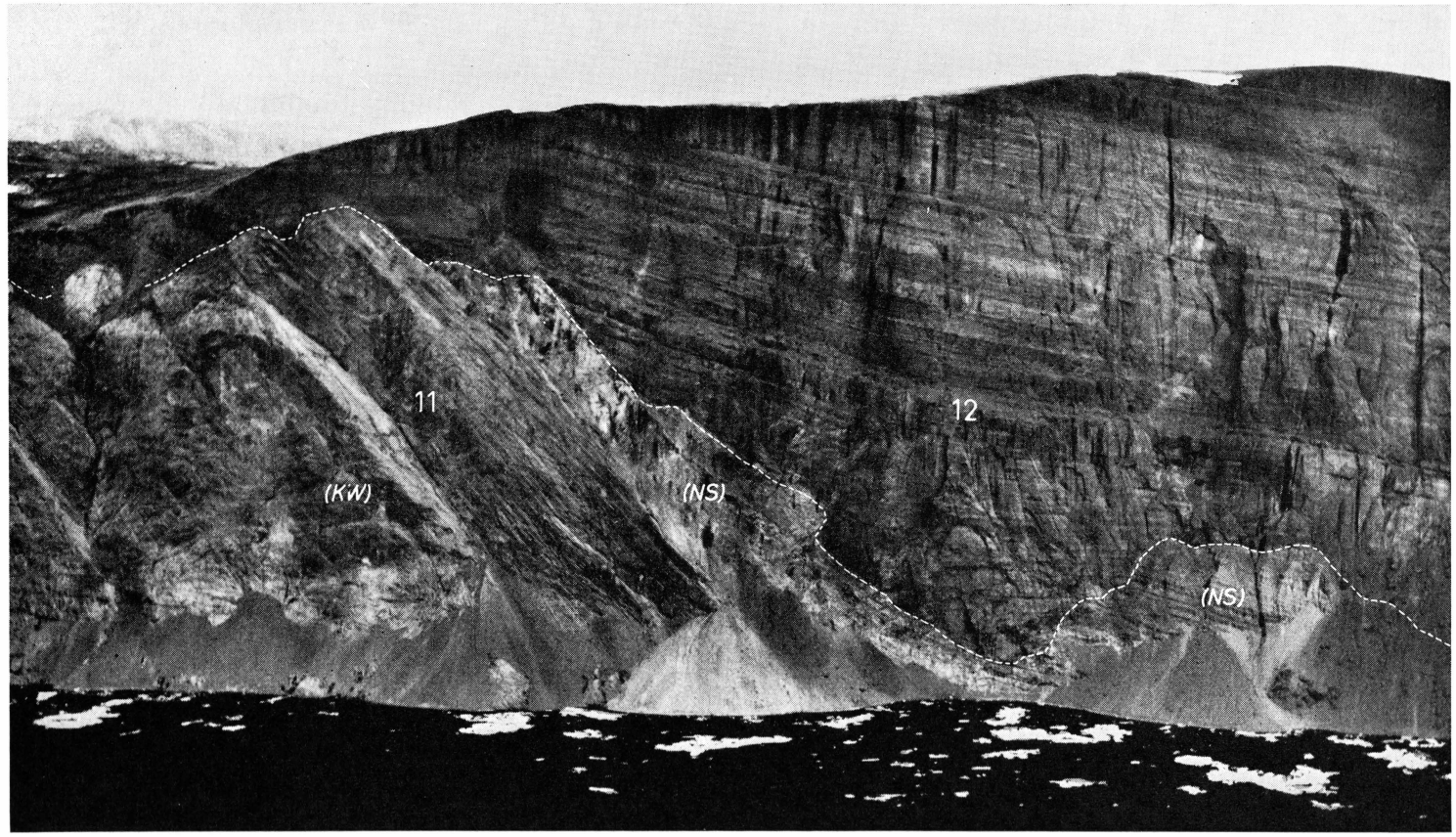


Fig. 55. South coast of Ella Ø at Narhvalsund showing the profound unconformity between Ordovician (11) and Middle Devonian Old Red Sandstone (12). The lowermost beds of the molasse pile have been tilted 40°, but the higher conglomerates have only a slight dip, indicating that the tightening of the Ella Ø anticline happened during the deposition of these Middle Devonian clastics.
Air-phot. F. SCHWARZENBACH, 1956.



Fig. 56. Late Caledonian granite batholith, southern Bartholins Land (74°15′ N), viewing east with Hudson Land in very background.
Air-phot. F. SCHWARZENBACH, 1956.

pressure in Hudson Land. Slices of the old Caledonian folded block, even of the gneiss complexes, were forced upward to pierce their own sedimentary mantle, which was then already considerably truncated

and covered by the basal beds of the molasse. A major structure initiated at that time is the "*Moskusoksefjord inlier*", which is situated close to the mouth of Moskusoksefjord (73°40′ N). The structure has been modified though by later intra-Devonian movements.

2) Folds and thrusts running northeasterly to north-northeasterly.

This pattern generally appears to be of younger age than the fold and thrust belts discussed above. In Hudson Land and the adjacent areas to the west (Ole Römers and Stenos Land) the northeasterly trending structures are predominantly of Upper Devonian age. Over the entire area, however, a widespread and multiple pattern of N–S faults preceded this folding and thrusting. *Graben structures* as well as antithetic *step-faults* resulted from this pattern. The throw of the faults amounted to several thousand meters (Plate XXXIII). In the course of the new spasm a mosaic of fault-bounded blocks was subjected to stress acting from east to southeast. Some of the former normal faults were rotated to become high-angle upthrusts and low-angle overthrusts as well. On the map the pre-thrusting horst and graben pattern is still revealed, to a certain extent, by northerly running strips of Old Red Sandstone downfaulted in between older rock units. Yet the superimposed movements remarkably disordered the original layout. This modification of the old pattern was intensified because the drive of the superimposed tectonics caused the new thrusts to run obliquely across these horst and graben blocks. For this reason in following one particular structure such as the prominent "*Nordfjord graben*" (cf. Map Sheet 3), the major remodelling shifted from one side of the graben structure to the other. In places the filling of the graben was squeezed and thrust upon the western abutment (Plate XXXIV, Fig. 57), in others the wall of the adjacent horst developed into a thrust and caused parts of the highground to lie upon the graben filling (Fig. 58). By comparing our photographs taken from various sections of the "*Nordfjord graben*" (Figs. 57–61) with the outline pattern shown on the Tectonic Map, it becomes evident that the Upper Devonian stresses caused quite a number of complicated faults, compound thrusts and slides of smaller magnitude.

Another fairly complex feature is the "*Klipperne structure*" in northwestern Hudson Land (Plate XXXV). There, it seems likely that the molasse filling of another northerly running graben structure was pushed under its western abutment until a marginal strip of the affected highground collapsed and slid eastward over the squeezed molasse pile.

Although most of these Upper Devonian thrusts and associated folds appear to drive westwards, in central and eastern Hudson Land prominent thrust sheets moved also eastwards (*e.g.* Nordhoeks Bjerg).

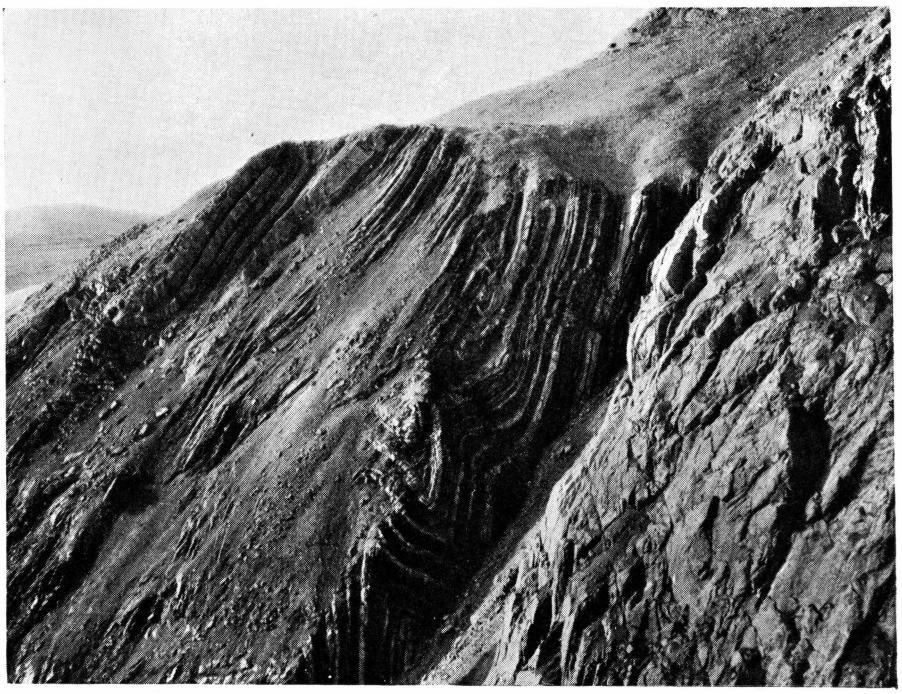


Fig. 57. Western boundary fault of the "Nordfjord graben" at Vibeke Gletscher (Ole Römers Land, 74°13′ N). The wall is made up of light-colored Ordovician limestones; the graben includes well stratified, multicolored beds of Middle to Upper Devonian. The conspicuous tectonic contact was formerly a normal fault, but was then rotated and made a thrust. The molasse filling of the graben was squeezed, crumpled and thrust against its western abutment. The photograph taken from helicopter shows the middle section of the scenery depicted on Fig. 60. — Phot. F. Schwarzenbach, 1956.

In Bartholins Land, which is situated west of the "Nordfjord graben", an old Caledonian complex of low to highgrade metamorphic rocks was sliced off by thrusts (Fig. 62). These low-angle faults, partly invaded by syntectonic intrusive granites, were evidently related to the Upper Devonian tectonics of Hudson Land. It is suggested, moreover, that another extensive belt of folds and thrusts, stretching southwesterly from Bartholins Land as far as the innermost nunataks around Hamberg Gletscher (73°30′ N), can be referred to this period, though no Old Red Sandstone was found to be involved there. This belt revealing young Caledonian mobility over a length of some 240 km is remarkably straight. At its eastern flank (Bartholins Land) syntectonic granites lubricated the westward drive of low-angle thrusts (cf. Fig. 52, Pls. XXVI, XXVII). In the middle section (northern Andrées Land and B. Studers Land) sheets of intrusive granite took part in the folding as plastic viscous

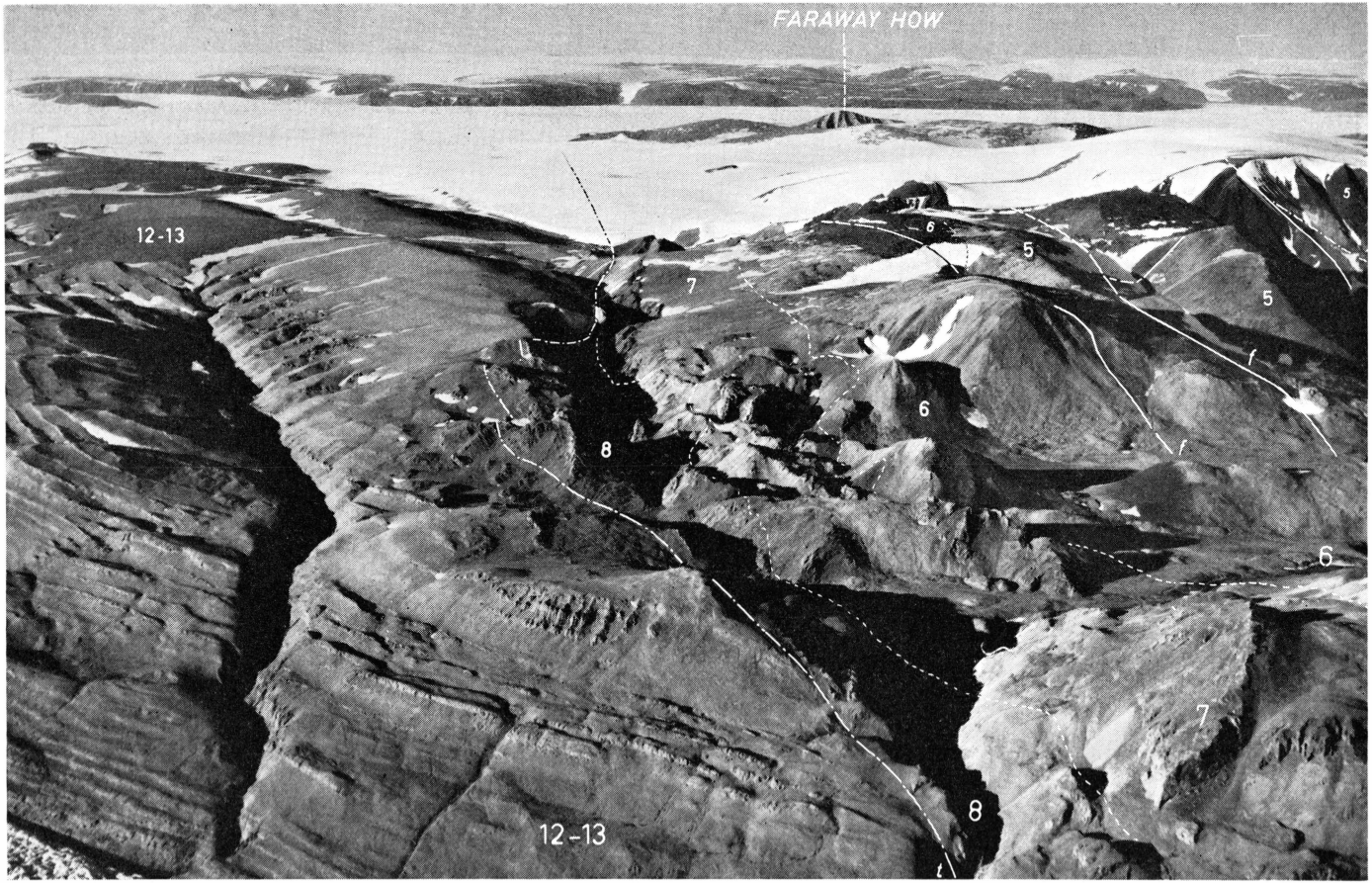


Fig. 58. Overthrust eastern edge of the "Nordfjord graben" in Stenos Land. — Air-phot. F. SCHWARZENBACH, 1956.

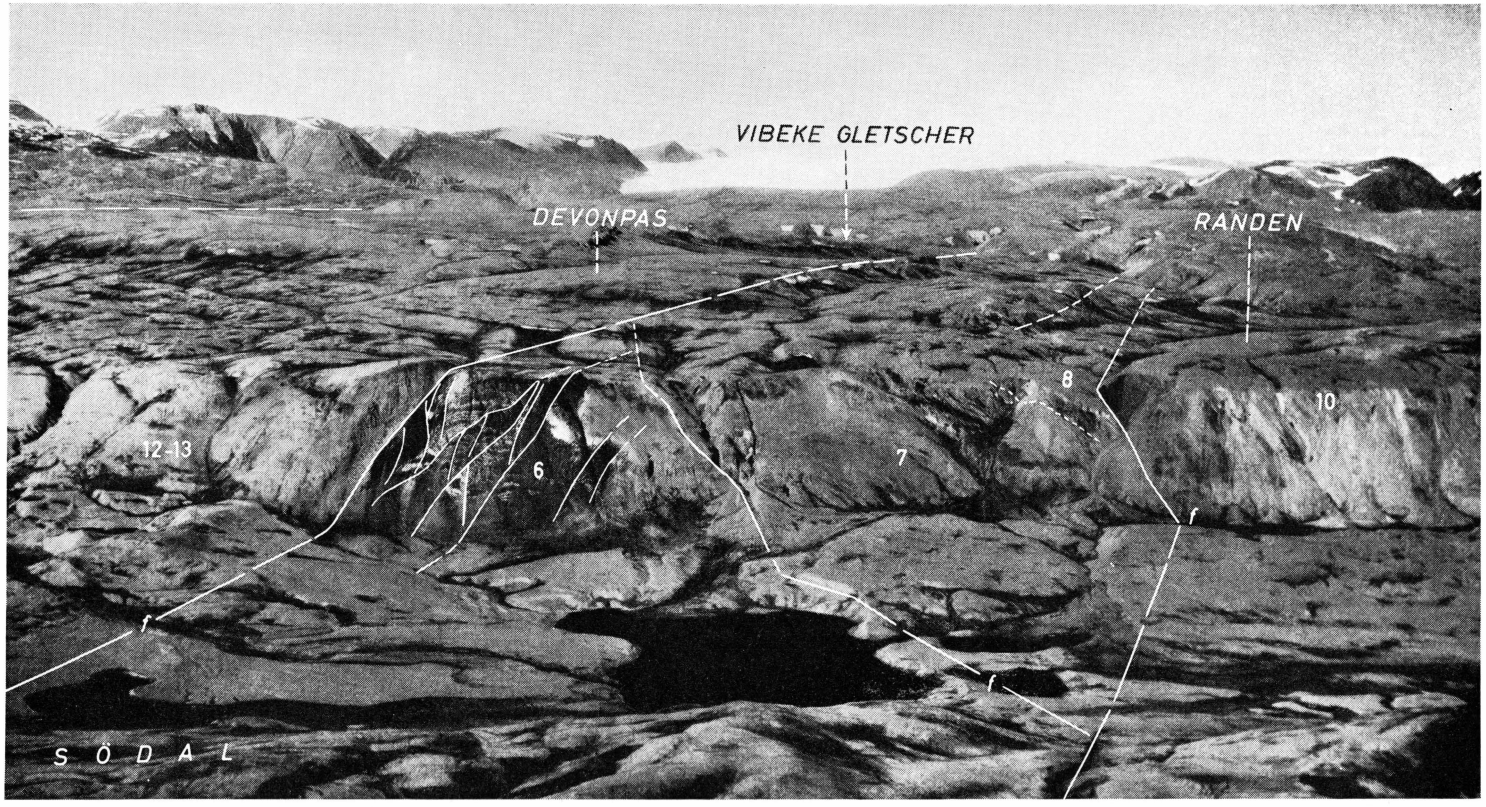


Fig. 59. Eastern edge of the "Nordfjord graben" in Ole Römers Land. 6 = Quartzite Series; 7 = Multicolored Series; 8 = Limestone-Dolomite Series; 9 = Tillite Group; 10 = Cambrian; 12–13 = Middle to Upper Devonian. Except for some effects of pinching the layout of the original fault pattern remained intact. This is in striking contrast to the area seen in the background (cf. Fig. 58) where Eleonore Bay beds were thrust over the down-cast molasse. — Air-phot. F. Schwarzenbach 1956.



Fig. 60. Western edge of the "Nordfjord graben" at the south side of Vibeke Gletscher. 11 = Ordovician; 12–13 Middle to Upper Devonian. The former normal boundary fault (*t*) developed into a high-angle thrust system. Along this marginal zone, the graben filling was intensely folded about axes plunging slightly toward northeast. — Air-phot. F. SCHWARZENBERG, 1956.

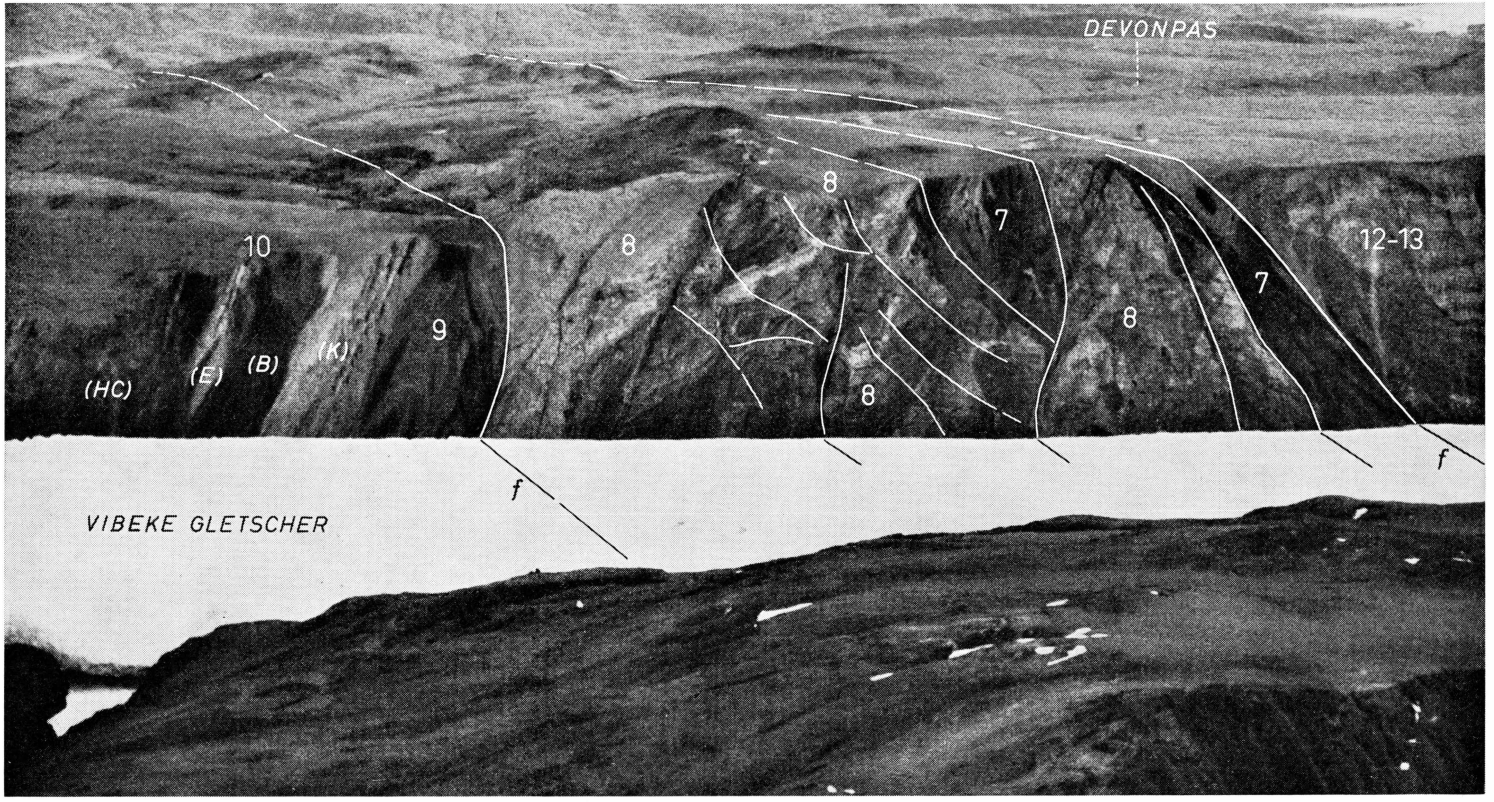


Fig. 61. Eastern edge of the "Nordfjord graben", south side of Vibeke Gletscher. 7 = Multicolored Series; 8 = Limestone-Dolomite Series; 9 = Tillite Group; 10 = Cambrian (including Kløftelv, Bastion, Ella Ø, and Hyolithus Creek Formations); 12–13 Middle to Upper Devonian. Both graben and highground remained fairly intact but much distortion occurred in the realm of the compound boundary fault. — Airphot. F. SCHWARZENBACH, 1956.

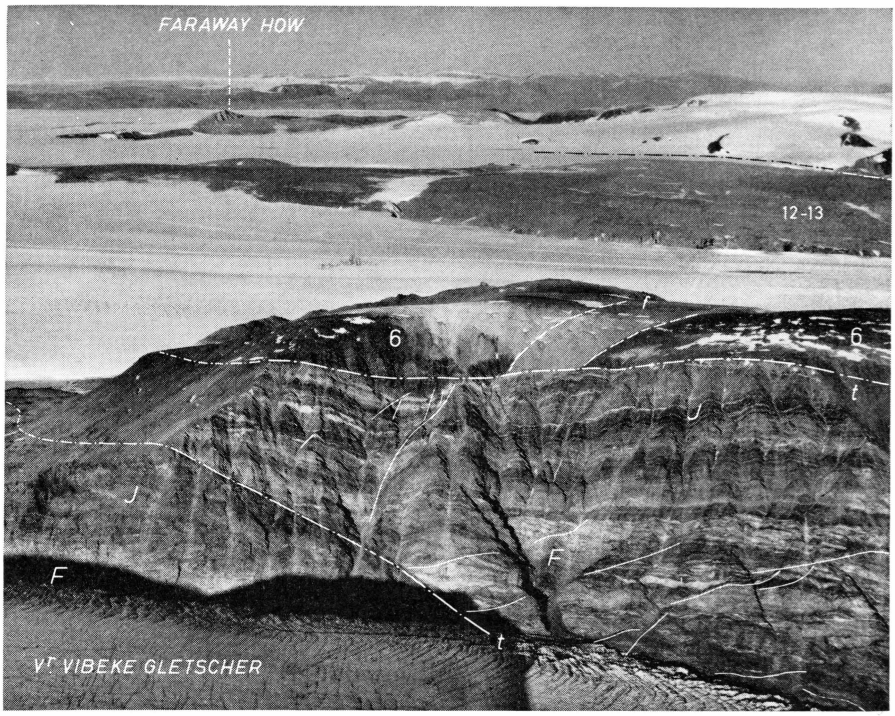


Fig. 62. Vibeke Nunatak (foreground) seen from the west. The middleground shows part of Stenos Land, where Eleonore Bay sediments were thrust over the downfaulted Old Red Sandstone molasse (12–13). At Vibeke Nunatak, in turn, Eleonore Bay quartzites (6), forming the stratigraphic base of the molasse beds, are thrust westwards upon metamorphic schists (*J*) and migmatitic gneisses (*F*). On the opposite wall of Vestre Vibeke Gletscher, in particular, syntectonic intrusive granites were found to be involved in related thrust structures (cf. Fig. 52). — Air-phot. F. SCHWARZENBACH, 1956.

masses (Fig. 63, compare also Figs. 49–51). In northwestern Andrées Land the superimposed thrust-fold belt involved also nonmetamorphic Eleonore Bay quartzites, which were thrown into asymmetric and recumbent structures (Fig. 64). From western Studers Land to central Mowinckels Land, the front of the young Caledonian belt is marked by a large-scale overthrust which is particularly well exposed around the 74th parallel, namely at Harald Griegs Fjeld (cf. H. R. KATZ, 1952b). In J. L. Mowinckels Land but also farther south in Louise A. Boyds Land granite intrusions of batholithic dimensions were emplaced posttectonically with respect to the major deformation along this belt of late Caledonian mobility.

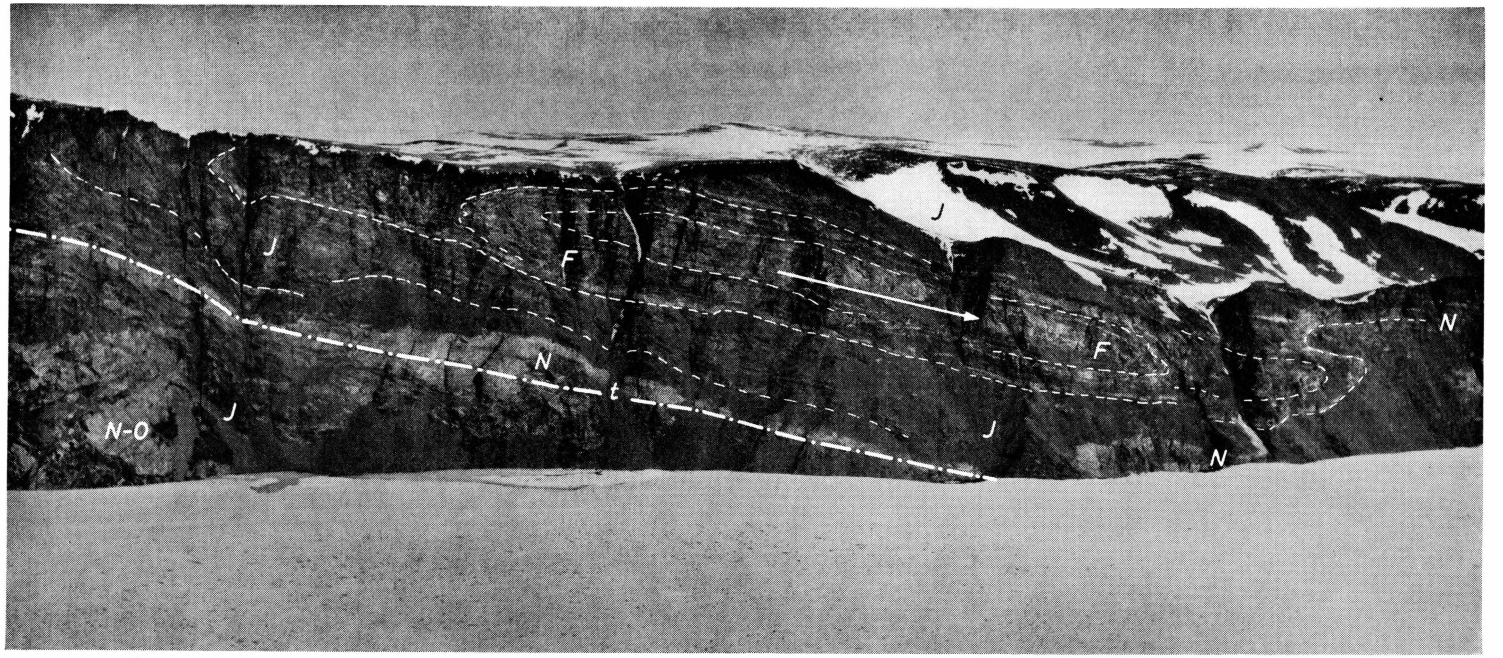


Fig. 63. Cliff at the south side of B. Studers Land showing a tight recumbent fold of banded gneiss (*F*) enveloped by micaschists (*J*). This structure may have originated from the old Caledonian architecture but was later partly reactivated and surrounded by a conformable sheet of intrusive granite (*N*). In the lower part of the outcrop, lubricating granites were emplaced also along a thrust (*t*). Approaching the left side of the outcrop the late Caledonian granites, however, become discordantly (*O*). — Air-phot. F. Schwarzenbach, 1956.



Fig. 64. Cliff at the northwestern tip of Andrées Land, view toward the heavily glaciated central part of that Land. The outcrop shows well stratified Eleonore Bay quartzites re-folded by young Caledonian movements and thrown into recumbent folds overturned towards the northwest. This structure largely parallels the significant thrust-system of Harald Griegs Fjeld, which lies right across the glacier seen in the foreground. — Airphot. F. SCHWARZENBACH, 1956.

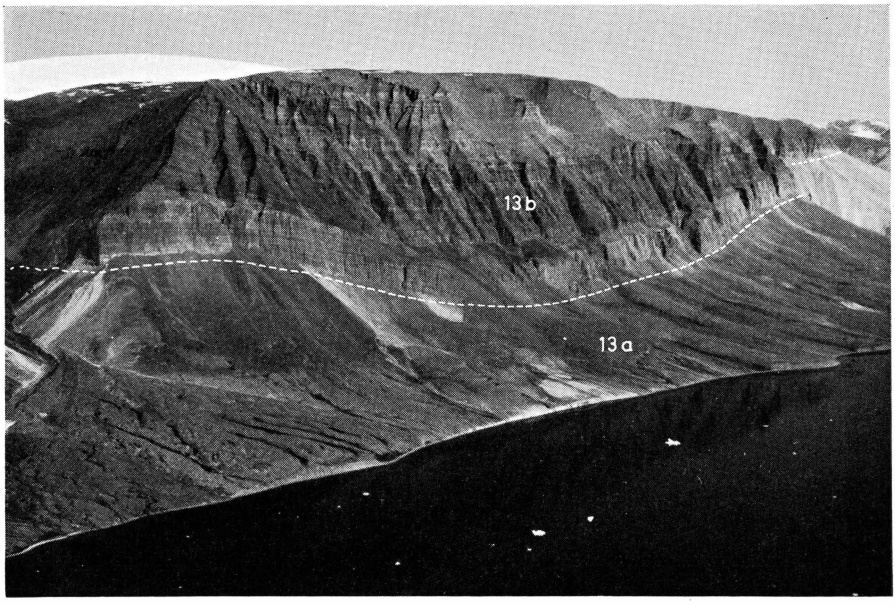


Fig. 65. Upper Devonian Old Red Sandstone thrown into very open folds by early Carboniferous movements. 13 a = "Kap Kolthoff Series", 13 b = "Kap Graah Series". Watsons Plateau (Gauss Halvø, 73°30′ N) seen from Kejser Franz Josephs Fjord. — Air-phot. J. HALLER, 1956.

C. Minor Succeeding Episodes

(Upper Paleozoic movements affecting the intramontane molasse deposits)

Early Carboniferous folds and thrusts in the Devonian molasse

After the deposition of the "Mount Celsius Series", that is the last cycle of Upper Devonian sedimentation, a shallow folding affected the Central East Greenland molasse basin. This evidently caused emergence again and a distinct break in sedimentation over a longer span of time in the Lower Carboniferous. The deposition of a new cycle of molasse beds, the "*continental Carboniferous*" began only after this period of tectonic unrest which produced a pattern of shallow folds and thrusts, all running meridionally across the Old Red Sandstone area. These structures are referred to as the "*Ymers Ø Phase*" by H. BÜTLER who considered them to represent 'posthumous Caledonian movements' (1935, p. 25), that is to say mere trailers of the Caledonian orogeny.

At the north coast of Kejser Franz Josephs Fjord, the Upper Devonian molasse pile appears in the form of a warped plateau (Fig. 65) rather than folded strata, and farther north, in Hudson Land, the ef-

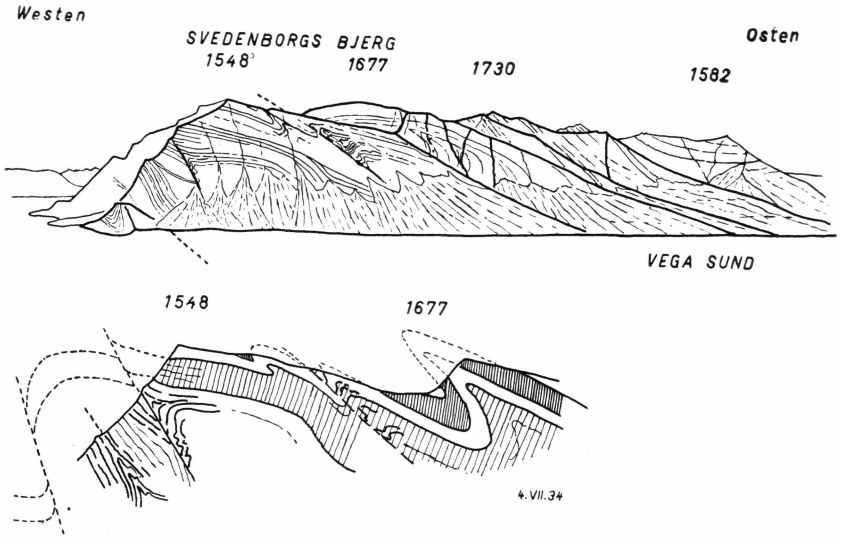


Fig. 66. Sketch and structure section of Svedenborgs Bjerg showing Middle Devonian molasse beds intensely folded and thrust by early Carboniferous movements. — Adapted from H. BÜTLER (1955, p. 60).

fects of these movements evidently fade away. But the southern area underwent remarkable distortion. Particularly in the western parts of Geographical Society Ø and Traill Ø crowded folds partly merge in a set of westward directed thrust sheets (Fig. 66). From Angelins Bjerg (Ymers Ø) to Syltoppene (northern Scoresby Land) the folding is entirely replaced by a thrust system that outlines the edge of the affected area (cf. H. BÜTLER, 1955, pl. 10). The mechanism that brought about this post-Devonian molasse folding might well be related to gravitational tectonics initially launched by fracturing and formation of northerly running horst elements off the present coast. Some preliminary thoughts on this relationship had been outlined by A. NOE-NYGAARD (1934, p. 70).

Upper Paleozoic continental sedimentation

1) Northeast Greenland

Carboniferous plants were first found in Northeast Greenland by members of the "Danmark Expedition", on Holm and Amdrup Land, between 80° and 81° N. The sparse material was determined to represent *Lower Carboniferous*[56]). There, the continental deposits form the base of an extensive plateau of post-Caledonian sediments which transgressed across the peneplaned fold complexes. The plant bearing succession is

[56]) A. G. NATHORST (1911).

conformably overlain by marine Upper Carboniferous (Moscovian) and Lower Permian (Sakmarian)[57]).

From Holm Land, the remnants of the sediment plateau stretch northeasterly across Kronprins Christian Land as far as the northern tip of Valdemar Glückstadt Land. Farther north a similar succession occupies the eastern tip of Peary Land (off the present map area). As a whole, Upper Paleozoic sediments accumulated here in a wide gulf, a shallow depression that came into being between the gradually vanishing Lower Paleozoic mountains of North and East Greenland. There are breaks in sedimentation indicating a back and forth motion of the sea. Post-Permian formations are sparse. Some Triassic beds occur at Peary Land, and late Mesozoic to Cenozoic beds are known from both Peary Land and the northern tip of Kronprins Christian Land.

On the Tectonic Map only the base of the blanket of Upper Paleozoic sediments is shown. In the area covered by Sheet 1, this base consists presumably everywhere of continental Carboniferous, reddish to light-colored sandstones. Yet south of the 80th parallel, the age of further beds also referred to the Upper Paleozoic is not known for sure. The small outcrops indicated on Hovgaard Ø (79°45′ N) and Lambert Land (79°08′ N) were spotted by aerial reconnaissance. This is also true for the large outcrop area of Hertugen af Orléans Land (78° N), plotted on Sheet 2. The outline of this occurrence—mainly hidden by the inland ice—is tentative and essentially based on significant morainic drift and sand-laden streams deriving from this area. In Nordmarken, I found large morainic blocks of red arkoses with fossil plants and imprints of drifted wood fragments; these erratics evidently were derived from the area concerned. Unfortunately no age could be obtained from these fossils[58]), and it is open to discussion whether these continental beds represent Carboniferous or Permian[59]) or neither of the two. At the south shore of Orléans Sund (77°50′ N), another occurrence of plant-bearing sediments was noted by members of the "Danmark Expedition"; at that time, however, this was held to be of ? Tertiary[60]) age. I tentatively referred these beds to the Upper Paleozoic.

In Northeast Greenland, as no traces of any late orogenic movements are revealed, the old Caledonian mountains evidently remained a stable block of land through all of the Devonian period. But by early

[57]) C. O. Dunbar *et al.* (1962).

[58]) By courtesy of Prof. T. M. Harris, the plant-bearing samples I collected in the summer of 1955 from boulders at Flyversø, Nordmarken, were examined at the University of Reading.

[59]) Based on the general appearance of these plant-bearing sediments Dr. H. Bütler (personal communication) suggested a Permian age as being most likely.

[60]) O. Bøggild (1917). Grönland, pp. 1–38, 6 figs., (*in* G. Steinmann and O. Wilckens, Handbuch der Regionalen Geologie, IV, 3), (Heidelberg).

Carboniferous time, through long-enduring and continuous erosion, the northern fold belts were finally worn down into low country. The lowlands, extending northwards from the slopes of the young Caledonian mountains, then became the site of continental sedimentation. The beds spread over this levelled land may be called a '*molasse*' as well. However, in contrast to corresponding formations in Central East Greenland where the stumps of mountain belts still formed protruded massifs inside an entirely continental environment, the Northeast Greenland molasse was "*external*", that is to say outside the still active and elevated mountain ground. Compared with the "intramontane" molasse formations the "external" accumulations were of inconsiderable thickness. Moreover, their originally continental environment was successively replaced by a southwards expanding Upper Paleozoic sea[61]).

2) Central East Greenland

In Central East Greenland, all Carboniferous beds were found to be of continental types. Although there is still a lack of uncontested fossil plant dating, it is assumed that here accumulation started only in Lower Namurian time, that is almost at the beginning of the *Upper Carboniferous*. The sediments, still a type of 'molasse' laid down in intramontane basins, are the waste products of the young Caledonian mountain ranges which were rather of fault-block types than folded mountains. Deposition developed continuously throughout Upper Carboniferous times lasting into the *Lower Permian*. The whole succession of Upper Paleozoic molasse amounts to a total thickness of 5,000 to 6,000 meters. As compared with the Old Red Sandstone it is remarkable to find no profound breaks in this pile. There existed numer ous centers of accumulation, mainly deltas of mountain streams which poured detritus from the western highlands into lacustrine basins. Thus a variety of fluviatile-lacustrine sequences developed, with intertonguing relationships but following each other largely conformably.

A slight angular unconformity was only found at the base of the coarse-clastic Lower Permian beds in the area south of Kong Oscars Fjord (see later).

On the basis of the present outcrop pattern, continental Upper Paleozoic beds are confined to a narrow belt some 370 km in length, stretching from Clavering Ø (74°25′ N) south-southwesterly across outer Kejser Franz Josephs Fjord, Ymers Ø, Geographical Society Ø, and Traill Ø

[61]) From this point of view, Dr. H. BÜTLER's suggestion of a Permian age of the plant-bearing beds at Hertugen af Orléans Land might well be right. The succession would then represent a belt of continental facies, at least around the 78th parallel, while north of the 80th parallel the environments were entirely marine since Upper Carboniferous times.

to Scoresby Land, from where continuous outcrops extend as far as the north shore of Scoresby Sund (71°15′ N). At Traill Ø, the belt attains its maximum width of some 30 km. But there, as well as south of Kong Oscars Fjord, there is clear evidence that Carboniferous molasse extends still farther eastwards, though transgressively overlapped by younger formations. To the west, the Carboniferous is generally bounded by faults and thus comes in tectonic contact with various older complexes, mainly the Old Red Sandstone. Everywhere, the Carboniferous beds have been dislocated along these faults, which are accordingly post-Upper Carboniferous in age. North of Kong Oscars Fjord, the western edge of Carboniferous sedimentation certainly extended far beyond these present border lines. In Scoresby Land, however, a mountain slope which almost coincided with the present major faults at the foot of the Staunings Alper massif, acted as the border of the elongated Carboniferous molasse trough.

Tectonics of the Middle Carboniferous to Lower Permian molasse formations

From the present distribution of Upper Paleozoic continental beds it is suggested that their depositional area was mainly a north-north-easterly running depressional zone, some 400 km long, and, in the southern part at least some 100 km wide. For the most part it occupied the same area as the Old Red Sandstone basin did. The principal basin axes, however, crossed each other at an acute angle. South of the 72nd parallel, younger molasse sedimentation extended westwards into the area of the former highground (structural province (3), cf. Fig. 40). From the layout of the early Carboniferous fold and thrust pattern described above it is suggested that the shift of the major belt of molasse sedimentation from a Devonian northwest to a Carbono-Permian north-northeast trend is the reflection of newly initiated block-fault tectonics. In the period of unrest referred to as the "Ymers Ø Phase", that is after the deposition of the Upper Devonian "Mount Celsius Series" and prior to the onset of the Middle to predominantly Upper Carboniferous molasse sedimentation, a *fundamental pattern* of fracture lines came into play: the "**post-Devonian main fault**", a north-northeasterly running fault zone[62]) along which the truncated Caledonides were successively drowned by the expanding realm of the Scandic maritime regime. This was brought about in late Paleozoic, but mainly in Mesozoic and Cenozoic times by repeated staircase displacements descending eastwards. It is interesting to note that

[62]) The fault zone, largely traceable from the Scoresby Sund region northwards through all of Central East Greenland was called "*Postdevonische Hauptverwerfung*" by A. VISCHER (1940, p. 154).

after the occurrence of the greatly varied structural features and directions in Devonian times extensive fractures took up once more the major trend of the old Caledonian mountain chain. But in doing so they also initiated a definitive submergence of considerable parts of the Caledonides. The north-northeast fracturing, first revealed by the "*Kong Wilhelm's line*" (pre-Grandjeans Fjord spasm, *i.e.* Lower to Middle Devonian) becomes now the predominant structural feature for all post-Devonian periods, not only in Central East Greenland but also in Northeast Greenland.

Due to *early Carboniferous fault block displacements* and related movements, in Central East Greenland, the Carboniferous molasse came to transgress across formations of different ages. In the northern part, on *Clavering Ø* the beds transgressed across deeply truncated Caledonian crystalline series (Plate XXXVI). This is also true for Passagehøje and Nordhoeks Bjerg in eastern Hudson Land. Farther south Carboniferous lies on Eleonore Bay beds as well as on Middle Devonian molasse (Salèvebjerg). On Gauss Halvø, in the area around "*Gastisdal graben*", it rests on the La Cours Bjerg injection complex, and in the graben itself on Middle and Upper Devonian molasse. From this it becomes evident that the "Gastisdal graben" began to subside prior to the deposition of the Namurian, though its major downthrow involving the Carboniferous molasse took place only in pre-Upper Permian times. South of Kejser Franz Josephs Fjord, the substratum of the Carboniferous is not visible, but it is likely to be mainly of Old Red Sandstone.

In Scoresby Land, however, Carboniferous molasse extends not much farther south than to the Tertiary intrusive complex of Werner Bjerge. The bulk of the molasse beds, south of the 72nd parallel all exposed along a compound fault zone at the foot of the Staunings Alper, was determined to be *Lower Permian* (E. KEMPTER, 1961). On Sheet 3, in the Mesters Vig area (72°10′ N), some younger molasse beds, tentatively referred to the Lower Permian, occur in the "Blydal graben", which is a post-Triassic structure. These beds overlie the Carboniferous with slight angular unconformity (E. WITZIG, 1954); the substratum is warped about northeasterly trending axes. Movements responsible for this distortion have been referred to as the "*Scoresby Land Phase*" (J. HALLER, 1961b). This folding is local and probably of minor importance as to Upper Paleozoic molasse tectonics. However, it coincides with the launching of molasse catching fault troughs in the Scoresby Sund region, which was until then rather the site of erosional processes than depositional environments.

At the turn of the Lower to the Upper Permian, taphrogenic movements of notable size and considerable extent occurred at various places. From Gauss Halvø the major downthrow of the "*Gastisdal graben*" has been

mentioned. This structure can be followed across eastern Hudson Land; farther north is appears to be the edge of the westwards sloping plateau of Carboniferous molasse at Clavering Ø (cf. Plate XXXVI). The tilting of that "*Clavering Ø fault block*" was demonstrated by A. VISCHER (1943, p. 156) to be of pre-Upper Permian age as well. Similar tectonic happenings—antithetic tilting of molasse-laden fault blocks—were also found in southern *Scoresby Land*, at the foot of the Staunings Alper, particularly around 71°30′ N. There, however, the beds involved are predominantly of Lower Permian age so that faulting and tilting can be dated as intra-Permian (E. KEMPTER, 1961, p. 25). Wherever these structures are traceable they represent a revival and further development of the Carboniferous north-northeasterly fault pattern already mentioned.

When the present fjord region of Central East Greenland became the site of the *Upper Permian sea* most of the intra-Permian fault escarpments were completely worn away (Plate XLIV). The landscape of Upper Paleozoic block mountain ranges disappeared and gave place to a worn down land surface which then was submerged. In the course of the process of profound Permian denudation considerable quantities of Upper Paleozoic molasse deposits must have been removed, particularly from the protruding edges of tilted fault blocks.

6. POST-CALEDONIAN BLOCK FAULTING AND THE TRANSGRESSIONS OF THE MESOZOIC SEA

The trunk-line of the old Caledonian fold belt was revived by a north-northeasterly running pattern of fundamental faults during Devonian but mainly during Carbono-Permian times. Repeated displacement along these compound faults was complemented by considerable denudation of the Caledonian mountain stumps. The fault block escarpments of Central East Greenland (at least in the area covered by Map Sheet 3) were planed down by the time the Upper Permian sea advanced from the east; this transgression brought to an end the Caledonian orogeny in Central East Greenland.

The conspicuous pattern of north-northeasterly trending fault blocks evident in Northeast Greenland (in the regions covered by Map Sheets 1 and 2) did not develop during the minor succeeding episodes of the Caledonian orogeny; rather, this faulting is regarded as a post-Caledonian event of Mesozoic or Tertiary age. Although copious exposures of Upper Paleozoic and Mesozoic strata are lacking in the northern regions, undisturbed Upper Paleozoic beds found in Kronprins Christian Land reveal the post-Lower Permian age of the faulting. We may conclude that the Caledonian drama came to its end first in the very north, where the Lower Carboniferous transgression set the final reference plane. Here, any distortion of this submerged peneplain should be considered as part of the post-Caledonian history.

The Upper Permian transgression

In Central East Greenland, evidently the heart of the ancient mountain range, vigorous crustal deformation ceased only in Lower Permian times. Here, the inundation by the Upper Permian sea marks the burial of the molasse-laden mountain trunk. Occurrences of marine Upper Permian beds are traceable from Hall Bredning (Scoresby and Jameson Land, 71°20′ N) to Wollaston Forland (74°25′ N), that is over a distance of 400 kilometers. Everywhere they overlie with angular unconformity older Paleozoic formations, including Caledonian crystalline

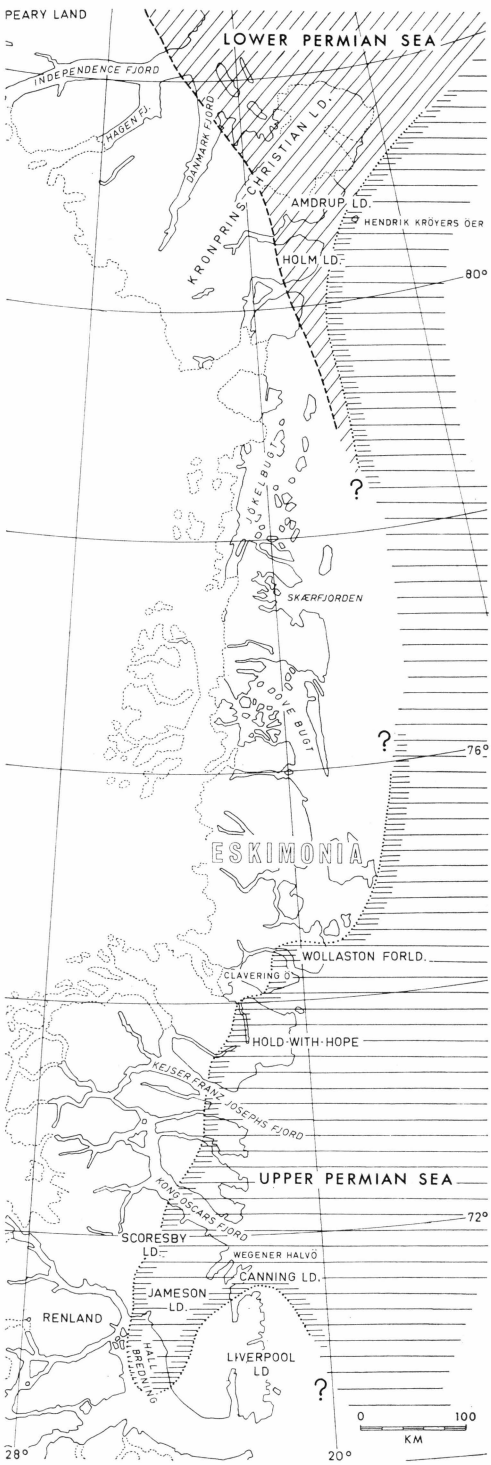


Fig. 67. Supposed coast lines of Permian seas in East Greenland. Modified after W. Maync (1961).

complexes. The marine Upper Permian attains a maximum thickness of 300 m and reveals a complex facies pattern. According to W. MAYNC (1942, 1961) eight different lithofacies members have been distinguished, all neritic to near shore accumulations. To MAYNC belongs the credit for having demonstrated that all these lithic units are intimately interlinked and obviously represent contemporaneous deposits laid down under different ecological conditions. The Upper Permian (Zechstein) age of these formations is based on a rich fauna of invertebrates[63]) as well as a significant fish fauna[64]).

For various reasons it is suggested that the Zechstein sea did not extend far beyond the Carbono-Permian fault zones, one of which crossed Godthaabs Golf (74°) stretching south-southeasterly across Hudson Land and Gauss Halvö ("*Gastisdal graben*"); the other followed approximately the foot of the Staunings Alper massif through Scoresby Land. At least at the beginning of the Zechstein, the shore of a shallow sea was close to both of these lines as is indicated by widespread basal conglomerates, in particular around Kap Stosch (northern tip of Hold-with-Hope), on Gauss Halvö and Scoresby Land. In the vicinity of Clavering Ø, the seaboard apparently swung towards the east (Fig. 67); on Wollaston Forland (74°25′ N) a sequence of near-shore redbeds is thought to indicate a proximate northern mainland (called "Eskimonia" by W. MAYNC).

That the *basal conglomerate* accumulated in an essentially marine environment is proved by both the presence of brachiopods and the gradual transition of coarse clastic to calcareous-dolomitic beds. The conglomerate is polygenetic. Around Kap Stosch, the formations are probably deltaic, poured in by streams from the near mainland. Yet in Scoresby Land[65]), where blocks of the size order of one meter are among the phenoclasts the formations are thought to represent *in situ* reworked substratum, that is to say mainly products of surf action during the advance of the sea across a lowland that was studden with continental debris. The warm Upper Permian shelf sea gave rise to organogenic *reefs* and related intraformational breccias. Limestone banks and reefs, in turn, locked-off *lagoons* and thus led to the deposition of *evaporites*, massive gypsum and gypsiferous shales.

On top of the Zechstein succession follow conformably ammonitiferous Lower Eotriassic beds (Scythian). In East Greenland, thus, the great turning-point in evolutionary history, the boundary between Paleozoic and Mesozoic, is possibly a transitional contact (R. TRÜMPY, 1960). From the viewpoint of the structural evolution of East Greenland,

[63]) O. DUNBAR (1955, 1961).
[64]) E. STENSIÖ (1961).
[65]) E. KEMPTER (1961, pp. 75–80).

a logical commencement of the new era would be the Upper Permian. In this paper, therefore, the Upper Permian shelf sea deposits are considered to represent the initial transgression of the Mesozoic sea. The Tectonic Map takes account of this fact in showing the base of both marine Upper Permian and Mesozoic beds in similar green shadings which differ only in their ruling. However, the area where Zechstein beds form the base of the post-Caledonian cover is confined to Map 3 and its adjacent southern terrains.

The fault-bounded basin of Triassic and Rhaeto-Liassic sedimentation

(The "Jameson Land basin" and its northward extension)

The transgression of the Upper Permian sea marked the end of the long-enduring Paleozoic diastrophism in Central East Greenland, but also re-established the marine regime, which lasted in the form of a fluctuating shelf-sea almost throughout the Mesozoic era. With this the Upper Permian seaboard (cf. Fig. 67) stands at the very beginning of the *development of East Greenland's present coast line and continental edge.*

From the section above it becomes evident that the Upper Permian shelf sea represented a period of quiescence. This pause, however, was of short duration. The coarse clastic character of some Eotriassic beds which include as well blocks of white Zechstein dolomite clearly points to a revival of Carbono-Permian fault scarps at the very beginning of Mesozoic times. Due to this new taphrogenic tendency a major basin structure was formed and gradually filled up, first by marine Eotriassic, then by marine to continental Middle and Upper Triassic and finally, by continental Rhaeto-Liassic.

The Triassic basin stretches north-northeasterly and its extent was fairly similar to that of Carbono-Permian molasse sedimentation. To the west the Triassic basin was bounded by a largely peneplaned highground of Caledonian folded rocks including Old Red Sandstone. From there detritus continued to be poured into the basin. Yet, in the Triassic, according to R. Trümpy (1961) sedimentary transport from an eastern highground is clearly indicated as well. In addition, slump structures are frequent in Triassic beds. The extent of this fault-bounded depositional area is estimated as of some 450 km in length and of 100 km in maximum width (Fig. 68). The formations accumulated from bottom to top can be characterized as follows:

(a) Marine *Upper Permian* (Zechstein), 200–300 m thick succession of lagoonal-neritic deposits.

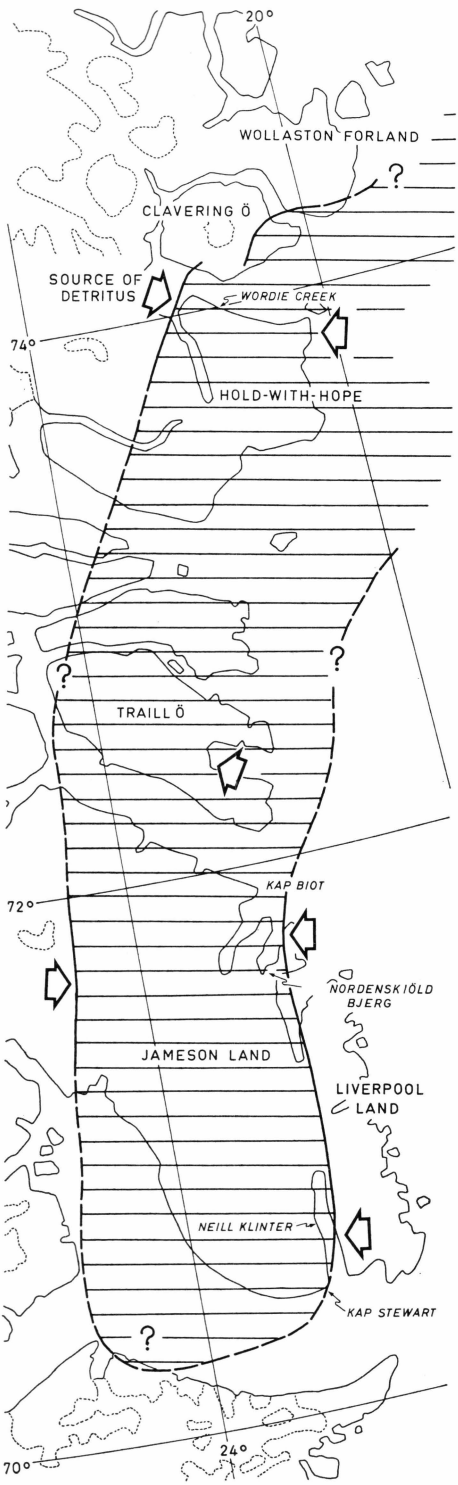


Fig. 68. Map showing the probable extent of the Eotriassic gulf in Central East Greenland. — After R. Trümpy and K. Grasmück (map presented at the International Geological Congress in Copenhagen, 1960).

(b) "*Wordie Creek Formation*" (Lower Eotriassic), marine succession, some 500–800 m thick, of mainly shales, sandstones, and in the uppermost part some intercalations of conglomerate, limestone and gypsum. From the type-locality, that is near Kap Stosch (Hold-with-Hope), eminent collections of invertebrates[66]) and vertebrates[67]) were obtained. The lower beds of the "Wordie Creek Formation" are among the oldest ammonite-bearing Triassic strata in the world. Their fauna is strikingly similar to that of the lowermost Triassic in the Himalayas and communication between the two regions was probably by way of East Asia and the Arctic Ocean. The Central East Greenland beds, however, represent only the oldest part of the Lower Triassic as is indicated by the occurrence of younger Lower Triassic horizons in the Canadian Arctic Archipelago. The Eotriassic sea of Central East Greenland formed a narrow gulf, opening to the northeast into the Arctic Ocean and having a blind southern terminus in the vicinity of the Scoresby Sund (see Fig. 68). During the deposition of the lower part of the "Wordie Creek Formation" (*i.e. Glyptophiceras* and *Ophiceras* beds) detritus was derived mainly from the western highground. Later on, the main supply came from a land mass to the east, of which Liverpool Land (70°30′–71°30′ N) and Canning Land (71°40′ N) are remnants.

(c) "*Mount Nordenskiöld Formation*", up to 700 m thick succession of raspberry-colored arkoses followed by shales, sandstones, beds of gypsum and "marls" (mudstones). These beds are likely to represent upper Eotriassic and part of the Middle Triassic. In western Jameson Land, the basal arkoses and sandstones (Rödstaken beds) were poured into the basin from western sources. But in eastern Jameson Land, the overlying succession of arkoses (*Paradigma* beds) are deltaic deposits, derived from the east. There, the laminae of current-bedding are uniformly inclined to the west, thus indicating sedimentary transport from the east.

(d) "*Cape Biot Formation*", up to 500 m thick succession of Middle to Upper Triassic beds, mainly thick-bedded red mudstones, including gypsum, shales, dolomites and sandstones. At the top there exists a continuous transition to the continental deposits of the Rhaeto-Liassic. Both the "Mount Nordenskiöld" and the "Cape Biot Formation" are mainly preserved south of Kejser Franz Josephs Fjord; both are essentially made up of *red beds*. Marine intercalations occur at several levels, and gypsum deposits and rock salt pseudomorphs indicate a temporarily high salinity in the land-locked basin. During the deposition of the

[66]) L. F. Spath (1930, 1935).
[67]) E. Nielsen (1961).

"Cape Biot Formation" only fine detritus was poured into the basin, but coarse sandstones reappear in the

(e) "*Cape Stewart Formation*", 200 m thick succession of light-colored, cross-bedded sandstones, of Rhaeto-Liassic age. There are two successive fossil floras[68]) present; they agree in type and sequence with similar floras in southern Sweden and Germany, and are there known to be successively of Rhaetic and Hettangian ages. In East Greenland, therefore, the Triassic-Jurassic boundary is not sharply defined. The facies of the "Cape Stewart Formation" is partly estuarine; the predominant depositional conditions were those of a swamp growing on mud flats, which must have been flooded by the sea from time to time. However, in northern Jameson Land, the marine intercalations appear to be more frequent than at the type locality at Hurry Inlet, where the formation also includes seams of coal. In southern Jameson Land, this continental accumulation is sharply terminated by marine basal beds of the

(f) "*Neill Klinter Formation*", another succession of about 200 m thickness, but of highly variable sandstones and shales, dated as Pliensbachian–Toarcian. These beds extend identifiably over all Jameson Land, and appear to thicken northwards. In southern Jameson Land, the top of the Toarcian sandstones is made up of a conspicuous bed of iron-stained quartz pebbles.

The withdrawal of the Liassic sea from the Jameson Land basin must have been rapid and complete, for the Toarcian is everywhere succeeded abruptly by transgressive beds of late Bathonian and early Callovian age. For almost two whole stages, the Bajocian and most of the Bathonian, there was no sedimentation within the present land area of East Greenland. This interval marks an important change in the paleogeography, for during late Triassic and Liassic times, sedimentation was restricted to the fault-bounded Jameson Land basin. From the Callovian onwards, Mesozoic transgressions invaded the East Greenland belt at least as far north as 77° N.

Triassic sedimentation in North Greenland

Only one occurrence of Mesozoic deposits is known from northern Greenland (J. J. TOELSEN, 1950, 1956). This is a *marine* sequence of **Lower to Middle Triassic beds** exposed at Herlufsholm Strand (East Peary Land), situated north of the area covered by Map Sheet 1. The succession was found to consist of two units of a total thickness

[68]) T. M. HARRIS (1961).

of 630 m. The fossil record of the shaly lower division indicates *Upper Scythian* age, that of the sandy upper division *Lower Anisian* age (B. KUMMEL, 1953). The whole sequence shows affinities to the Triassic of the Canadian Arctic, British Columbia as well as to those of Spitsbergen and Siberia. It is quite different, however, from the Triassic of Central East Greenland, where beds of similar stages are either missing or represented by the poorly fossiliferous "Mount Nordenskiöld Formation" mentioned above. The extent of this incursion of the Lower Triassic sea in Northeast Greenland is not known, although it seems likely that there existed no direct sea way to the fault-bounded gulf of Central East Greenland.

The transgression of the Middle Jurassic

It is remarkable that the Lower Jurassic fossil faunas preserved in East Greenland differ little from those of northwestern Europe; the Upper Jurassic again is characterized by faunas of typically northwestern European aspect. East Greenland's *Middle Jurassic*, however, differs greatly in this respect, for its nine successive ammonite faunas[69]) are peculiar to the Arctic (*Boreal realm*) and can be correlated with the European only at the top of the succession. D. T. DONOVAN (1957, pp. 164–65) called attention to this fact and postulated that the connections between northwestern Europe and Greenland were closed at that time, either by dry land, or by areas of non-marine sedimentation. This corresponds largely to the view of J. W. ARKELL (1956, pp. 606–15) who argued from more general considerations that during the Bajocian and Bathonian there was a remarkable regression of the sea from most of the known world which is now land (perhaps due to a deepening of the Pacific?, see *op. cit.* p. 641). For the rest only northwestern Europe and the Tethys were left still inhabited by ammonites, while in some places a land or swamp regime was established. ARKELL thought that it was during this regression that the Arctic Ocean was cut off from the seas of the rest of the world and the special Boreal fauna began to evolve. Then, the Callovian, but also the Lower Oxfordian and Lower Kimeridgian were characterized by great expansion, enrichment and spread of Boreal genera. ARKELL pointed out that it is with the beginning of the Callovian that peculiar endemic Boreal faunas first appear, brought south over the surrounding lands by transgressions spreading from the Arctic Ocean.

In an attempt to form an idea of the distribution of land and sea in the Arctic at the beginning of the Callovian stage, DONOVAN furnished

[69]) J. H. CALLOMON (1959, 1963).

his paper a with paleogeographic map (*op. cit.* pl. 2), assembling all data available: from the Arctic Ocean evidently a long, blind inlet stretched through the extreme northwest of Canada into the western interior of the United States. In the neighborhood of North America's present west coast a parallel arm of the sea is suggested. From the Arctic Ocean the Callovian sea also transgressed across Prince Patrick Island into the Canadian Arctic Archipelago. In Greenland, the sea apparently just overlapped the eastern edge, the coast being presumed to continue southwards from Scoresby Sund. The Barents Sea was at least partly submerged, although the northern part of Svalbard was above sea-level. The existing reconstructions of the eastern side of the Atlantic, however, DONOVAN (*op. cit.*) found less satisfactory; he particularly doubted the existence of a large continental block "*North Atlantis*"[70]), lying to the north and west of the British Isles. In DONOVAN's view, during the Mesozoic era, the stumps of the Caledonian belt and the newly truncated chain of the Variscian mountain system provided highlands acting as barriers at the northwestern edge of Europe so that direct sea routes were temporarily closed to migrating faunas.

In Central East Greenland, the record of Jurassic formations is largely complete except for a significant break in sedimentation at the top of the Liassic extending into the Bathonian. Although here the Jurassic was a time of almost complete quiescence, this interval of non-deposition reflects a considerable oscillation of relative sea-level over the whole area. All Jurassic biofacies, however, indicate *shallow water environments*, ranging from sublittoral marine through lagoonal and brackish, even to swamps which have left coal seams of economic size[71]). Environments of the latter type have already been mentioned from the Lower Jurassic at Hurry Inlet ("Cape Stewart Formation", Rhaeto-Liassic), but comparable formations occurred once more in Upper Jurassic times, though much farther to the north, namely at Hochstetters Forland (75° N) in the "Muschelbjerg Formation" (Oxfordian or Kimeridgian) and at Sælsøen (77° N) and Annekssöen (77°30′ N); the latter two occurrences are represented however, by undetermined formations of either Upper Jurassic or Jurassic-Cretaceous age.

Although in Middle and Upper Jurassic times the sea encroached along Greenland's east coast over considerable land areas, the recurrence of two predominant sedimentary types throughout the succession indi-

[70]) According to L. J. WILLS (1951, p. 7) "*North Atlantis*" is a paleo-continent whose existence is evidenced in British strata from early Paleozoic to mid-Cretaceous times.

[71]) For local use by Greenlanders, trappers and expedition boats (during the nineteen-thirties some steamers made their way home with a supply of Greenland coal), cf. H. FREBOLD (1932, pp. 56–63).

cates the persistence of a very limited selection of environments; sedimentation off a steep, often faulted coastline, backed by a mountainous hinterland, is believed responsible for the *light-colored sandstones* and the *black shales* (DONOVAN, *op. cit.* pp. 116–21). Yet a few narrow belts of conglomerates are present along submarine fault-scarps. Limestones, however, are rare and insignificant throughout the Jurassic formations.

The *sandstone facies* is particularly well exemplified by the basal sequence of the Middle Jurassic transgression, that is the "*Yellow Series*"[72]) (Upper Bathonian, Callovian, Middle Oxfordian[73]), which extends from Jameson Land (71° N) to Store Koldewey Ø (76° N). It consists of quartz sandstones, sometimes well cemented with calcite. The usual colors are white to grey and yellow, but brown and red sandstones also occur. Many beds are micaceous although other sections are remarkable for their purity. Conglomerates and coarser clastic beds may occur, especially at the base of the succession. There is a good deal of varied structure in the sandstones; the beds are often massive, less commonly thin-bedded and platy and cross-bedding is often developed. Fossil wood and impressions of plants, usually unidentifiable, are frequent in the sandstones. Marine fossils occur only at a few horizons where they may be fairly abundant, although often poorly preserved.

Outcrops of Middle and Upper Jurassic age stretch over most of Central East Greenland's present coastal area, but they are evidently absent from the area between 73°30′ N and 74°10′ N, that is from Gauss Halvø and Hold-with-Hope. There, Cretaceous beds (Aptian and Younger) rest directly on the Eotriassic. According to DONOVAN (1957, p. 106) it is open to discussion whether the absence of Jurassic rocks over this area is due to non-deposition or to pre-Aptian denudation. There is no proof, such as shore-line facies, that there was a landmass projecting

[72]) The term "*Yellow Series*" ('Gelbe Serie') was suggested by W. MAYNC (1947, p. 120) for the transgressive lower succession of the Middle to Upper Jurassic cover rocks between lats. 74° and 75° N; D. T. DONOVAN (1953, p. 18), adopted the term for stratigraphically and lithologically equivalent beds between lats. 72° and 73° N. The same term, however, had been previously applied to an exceptional facies of the Aptian at the north coast of Hold-with-Hope by L. KOCH (1931, p. 46). In agreement with Dr. L. KOCH, the term "Yellow Series" was henceforth restricted to the Jurassic formation. It is remarkable, however, that the sandstone facies of the Aptian in northern Hold-with-Hope ('Yellow Series' of KOCH, *non* MAYNC) is so similar to the Jurassic "Yellow Series" that MAYNC said that he could not distinguish between them on the basis of lithology (MAYNC, 1949, p. 131).

[73]) W. MAYNC (1947, p. 126) attributed the "*Yellow Series*" to the Upper Bathonian, the Callovian, and the Argovian (Neo-Oxfordian). D. T. DONOVAN (1957, p. 39) doubted an upward extension of the series into the Lower Oxfordian and confirmed only an Upper Bathonian and Lower Callovian age. More recent investigations carried out by J. PUTALLAZ (1961, p. 53) on Traill Ø, however, led to the assumption of a Middle Oxfordian age for the top strata of the "Yellow Series".

from the western highground into the Middle and Upper Jurassic sea at this place. On the other hand, however, MAYNC (1947, pp. 142–45) claimed positive evidence for postulating such land, called "Neo-Eskimonia" (Fig. 69). This hypothetical swell separated the shelf sea into a southern and a northern depositional area.

The southern area includes the "Jameson Land basin" as a major site of sedimentation. Clasts within the Jurassic conglomerates and coarse sandstones indicate a provenance of Upper Paleozoic molasse beds along the western boundary of the basin. The eastern edge of the basin evidently ran through Liverpool Land; the absence of coarse detritus along this paleo-shoreline indicates that the crystalline rocks of the Liverpool Land block and its presumed northward extension were not an important source of sediment. A salient feature of the deposits in the "Jameson Land basin" is the change from a thin argillaceous facies, the "*Vardeklöft Formation*", in the south-east to the thicker, largely arenaceous development or "*Yellow Series*" north of Hurry Inlet. The series attains its greatest thickness of some 1,300 m at Traill Ø (J. PUTALLAZ, 1961, p. 53). There, the basal conglomerates and breccias transgress across the Middle Triassic. The upper part of the series consists of coarse sandstones partly of continental origin and partly laid down in a littoral environment. For the first time since the Triassic there was an extension of the depositional area north of Kong Oscars Fjord, at least as far north as Kejser Franz Josephs Fjord. It is hard to say whether this part of the basin was in direct connection with the sea to the east, or not. However, if DONOVAN (1957, pp. 102, 109) is correct in his hypothesis of a northward extension of the Liverpool Land block, postulated for Oxfordian and Kimeridgian times, this barrier probably existed also during the Callovian. Thicknesses and facies of the "Yellow Series" suggest that the basin structure opened to the south: the sandy deltaic deposits accumulated to their greatest thickness in the Kong Oscars Fjord region, become thinner southwards, and pass into shales nearer the mouth of the basin that is at the present entrance of Scoresby Sund.

In the *northern region*, extending northwards from the hypothetical landmass "Neo-Eskimonia" to the 77th parallel (cf. Fig. 69), the "*Yellow Series*" is the earliest Jurassic formation. On Clavering Ø it overlaps the Eotriassic, farther north it comes to lie unconformably on Caledonian crystalline rocks. The principal outcrop of the "Yellow Series" is in Wollaston Forland, with extensions into Clavering Ø and Kuhn Ø. To the west it is bounded by fault lines, which formed at the close of the Jurassic. Towards the east the clastic beds evidently wedged out against the gentle slope of a tilted block (Fig. 70). In this area the accumulation of the "Yellow Series" took place in a narrow basin elongated north-

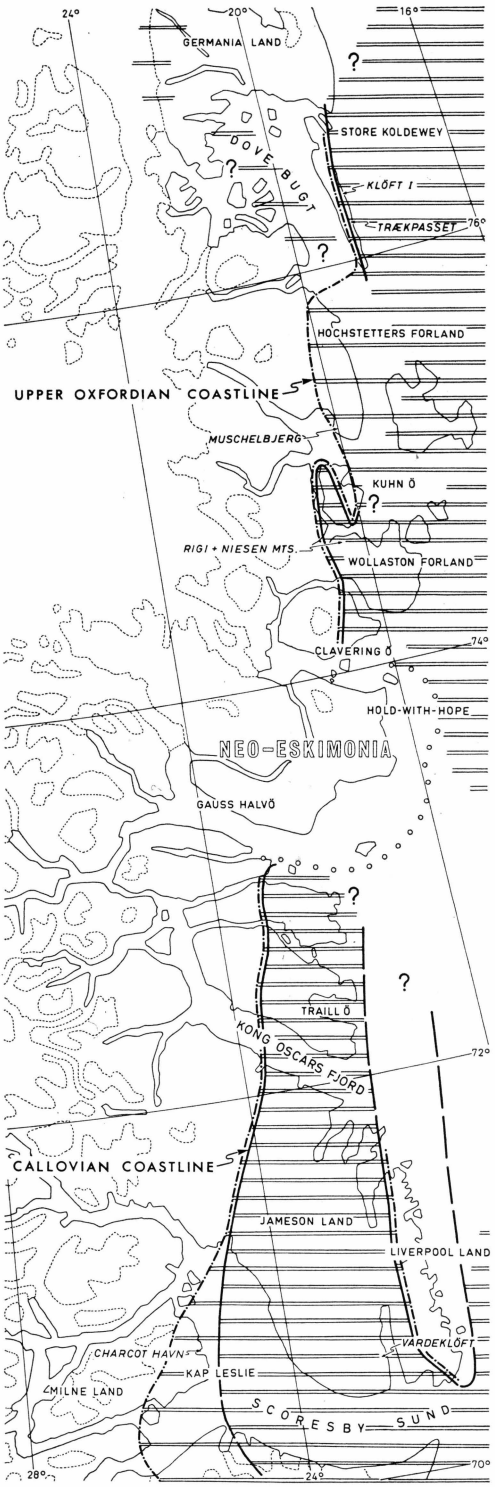
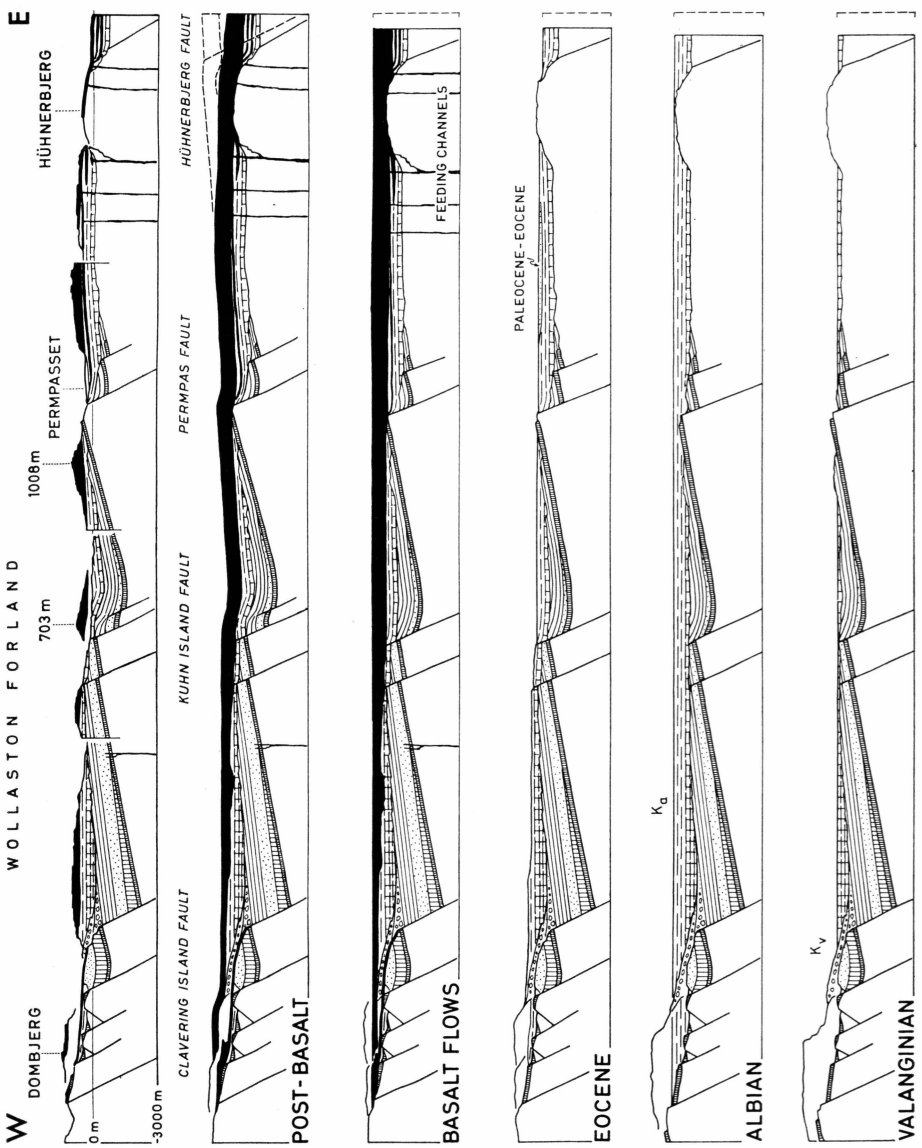


Fig. 69. Map showing the probable coastline of Central East Greenland in Callovian and Upper Oxfordian time. — After W. Maync (1947) and D. T. Donovan (1957).


W
E
WOLLASTON FORLAND
DOMBJERG
703 m
1008m
PERMPASSET
HÜHNERBJERG
0 m
-3000 m
CLAVERING ISLAND FAULT
KUHN ISLAND FAULT
PERMPAS FAULT
HÜHNERBJERG FAULT
POST-BASALT
FEEDING CHANNELS
BASALT FLOWS
PALEOCENE-EOCENE
EOCENE
K_a
ALBIAN
K_v
VALANGINIAN

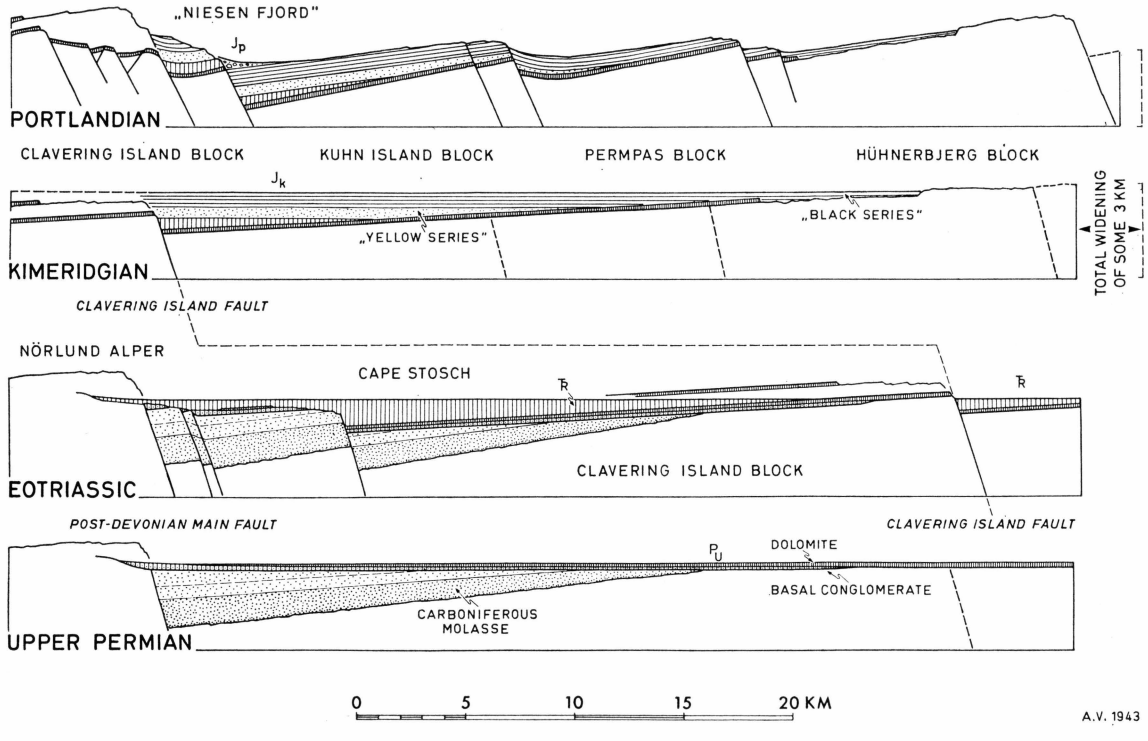


Fig. 70. Consecutive sections of the post-Caledonian block faulting in the region between 74° and 75° N. After A. VISCHER (1943, pl. 6).

south, open to the south but probably not to the north. The northern and eastern edges of this local basin would thus have been formed still by remains of MAYNC's land "*Eskimonia*", which had been an area of emergence during the late Paleozoic, the Triassic, and the Lower Jurassic. At Store Koldewey Ø, the present Callovian deposits ("*Trækpas Formation*") are distributed along a narrow strip at the foot of a fault scarp that runs north-south throughout the island. These beds mark the westward limit of the Jurassic sea at this place. Yet the sea might well have penetrated farther westwards to form a narrow inlet following the dipslope of a gently tilted block; at present, however, most of the area concerned lies largely below sea-level.

The facies of the "*Yellow Series*" in the northern region is similar to the sandstone facies in the south, and may be interpreted also as deltaic formations deposited by rivers discharging from the highlands, principally from the west. The coarse and variable nature of these beds, the absence of marine fossils throughout the greater part of the thickness, and the abundance of plant remains and drifted wood are in accordance with such an origin. But there are occasional horizons with ammonites and other marine shells, suggesting that periodic subsidence allowed incursions of the sea. On the basis of the absence of deposits dateable to the Middle and Upper Callovian or Lower Oxfordian, DONOVAN (1957, pp. 108–09) assumed that there was a break in sedimentation during that time. The alternative view, that there was continuous sedimentation through Middle and most of the Upper Jurassic, is held by MAYNC (1947, pp. 184–85) and has been supported once more by PUTALLAZ (1961, pp. 53–54).

In Upper Jurassic times, both the northern and southern areas were enrolled in a fully and continuously marine environment essentially of *black shale facies*. These beds were apparently deposited in quiet water under reducing conditions, not necessarily at great depth. It is generally accepted that a black shale facies denotes sedimentation in basins with poor water circulation, which are usually connected with the open sea by shallow channels only. DONOVAN (1953, p. 65; 1957, pp. 120–21) suggested that such basins had been formed, indeed, off East Greenland's Mesozoic seaboard.

At that time the structure pattern was obviously dominated by a few major faults separating slightly tilted blocks which paralleled the coast (cf. Fig. 70). Although the eastern flanks of these blocks remained at least partly above sea-level, basins with restricted outlets were created along the drowned western sides. In addition, the elevated edges of blocks farther west, lying close to the shore, may have acted as barriers to rivers carrying sediments from the Mesozoic mainland, so that coarse material was denied access to the sea except at a few places. Black shales consti-

tute the greater part of the "*Black Series*" (Upper Oxfordian, Lower Kimeridgian) and the "*Kuhn Beds*" (Upper Kimeridgian). These successions may be extremely uniform, as is the "Black Series" of Triall Ø, where about 500 m of shales are exposed without interruption (DONOVAN, 1953, pp. 28–29). Fossils, however, are to be found only at occasional horizons. They are chiefly ammonites, which may have been free-swimming of surface living animals, and a few genera of lamellibranchs which appear to have been able to live on a muddy, somewhat oxygen-deficient bottom. The normal bottom-dwelling fauna is absent.

Both to the north and to the south of the eastwards projecting landmass "Neo-Eskimonia" there was the same distinct change in sedimentation from the "Yellow" to the "Black Series". Yet in the northern region there exists a transitional succession of some 40 m of sandy shales intercalated by minor beds of coarse clastics, together called the "*Grey Series*" (MAYNC, 1947, pp. 127–28). In both areas the change of sedimentation evidently coincided with an expansion of the sea.

The Jurassic-Cretaceous interregnum was a period of profound erosion. Formations recording this time interval are not abundant; most of our knowledge comes from Milne Land in the very south, and to a lesser extent, from the Wollaston Forland region to the north. At the eastern tip of **Milne Land** (Charcot Havn, Kap Leslie, 70°40′ N)[74]), the Upper Oxfordian transgressed with a basal conglomerate ("*Charcot Bugt Sandstone*") across a pavement of Caledonian gneisses. The conglomerates were gradually followed by sandstones, arkoses, and clays ("*Cordioceras Shales*" of proven Upper Oxfordian age). On the top of these we find again a sandstone formation ("*Pecten Sandstone*") conformably overlain by black, micaceous clays and marls, the "*Kimeridgian Clays*" (Lower and Upper Kimeridgian). In the northern area the occurrence of Upper Oxfordian and Lower Kimeridgian sediments are scattered and disconnected outcrops spread over an area including Wollaston and Hochstetters Forland (*e.g.* the coal-bearing "*Muschelbjerg Formation*", cf. p. 148) as well as Store Koldewey, where Kimeridgian sandstones were found conformably on top of the Callovian beds but also transgressively on Caledonian gneiss.

Late Jurassic block faulting and related features

The comings and goings of the Jurassic sea were mainly due to eustatic changes in sea-level; yet minor movements of fault blocks forming low land barriers off the coast have to be considered as well. Except for the superposition of Volgian[75]) (*i. e.* Portlandian) conglomerate

[74]) See D. T. DONOVAN (1957, pp. 40–44); J. H. CALLOMAN (1961, pp. 263–64).

[75]) In East Greenland, the formations near the Jurassic-Cretaceous boundary can be dated best in terms of the succession in the Volga Basin of Russia.

beds[76]), which are traceable on western Kuhn Ø and northern Wollaston Forland, no angular unconformity has been recognized between any of the Jurassic formations. This indicates that the marginal part of the continent remained fairly stable throughout this time. At the close of the Jurassic, the period of quiescence was brought to an end by considerable fault displacement[77]) which was probably the most important event during the Mesozoic in East Greenland (cf. Fig. 70). The faulting resulted in an angular unconformity which is almost everywhere present where Volgian or younger formations overstep Kimeridgian or earlier rocks.

The land barrier "*Neo-Eskimonia*" probably existed through all of Jurassic time. North of it the late Jurassic to early Cretaceous sea was bounded on the west by prominent fault cliffs, which came into being in the Lower Volgian. The process of shifting of fault blocks lasted, however, through Berriasian and Valanginian times as well. The specific conditions of sedimentation in the domain of the late Jurassic "*Niesen Fjord*"[78]) have been dealt with in a rather detailed account by W. MAYNC (1947). This paleoinlet is the only place where these important late Jurassic block fault movements can be dated stratigraphically, for along the new faulted coastlines a conspicuous series of coarse clastic detritus was laid down. Close to the fault face, breccias were dumped, often with enormous constituent blocks, while farther from the shore conglomerates and sandstones accumulated. These largely syn-tectonic deposits were laid down with strong unconformity on the Jurassic and older rocks (Fig. 71).

[76]) These coarse clastic beds accumulated from Lower Volgian through Lower Valanginian were collectively named "*Rigi Series*" by W. MAYNC (1947, 1949; see also MAYNC's statement on the geological map pl. 6, *in* L. KOCH's report of 1950). In the summer of 1957, D. T. DONOVAN re-examined the type area, *i.e.* Rigi Bjerg in northwestern Wollaston Forland. In a paper of 1964 DONOVAN showed that the "Rigi Series" and the "*Lower Niesen Beds*" (Lower Valanginian) were one and the same formation. Yet both in northwestern Wollaston Forland and on western Kuhn Ø, DONOVAN found another group of clastic beds (associated with MAYNC's "Rigi Series") to lie below, and to be differentiated from, the "Niesen Beds". DONOVAN (*op. cit.* pp. 15–16) named this basal succession, which clearly includes beds equivalent to the top of the Lower Volgian, "*Laugeites Beds*" (yielding Perisphinctidae of genus *Laugeites* Spath, 1936).

[77]) These movements occurred contemporaneously with the principal phase of Nevadan orogeny that affected the western side of North America from Alaska to California.

[78]) "*Niesen Fjord*" (MAYNC, 1949, p. 213) was a narrow arm of the Volgian (Portlandian) sea which stretched northwards from the present-day Wollaston Forland across Lindemans Fjord to Fligelys Fjord.

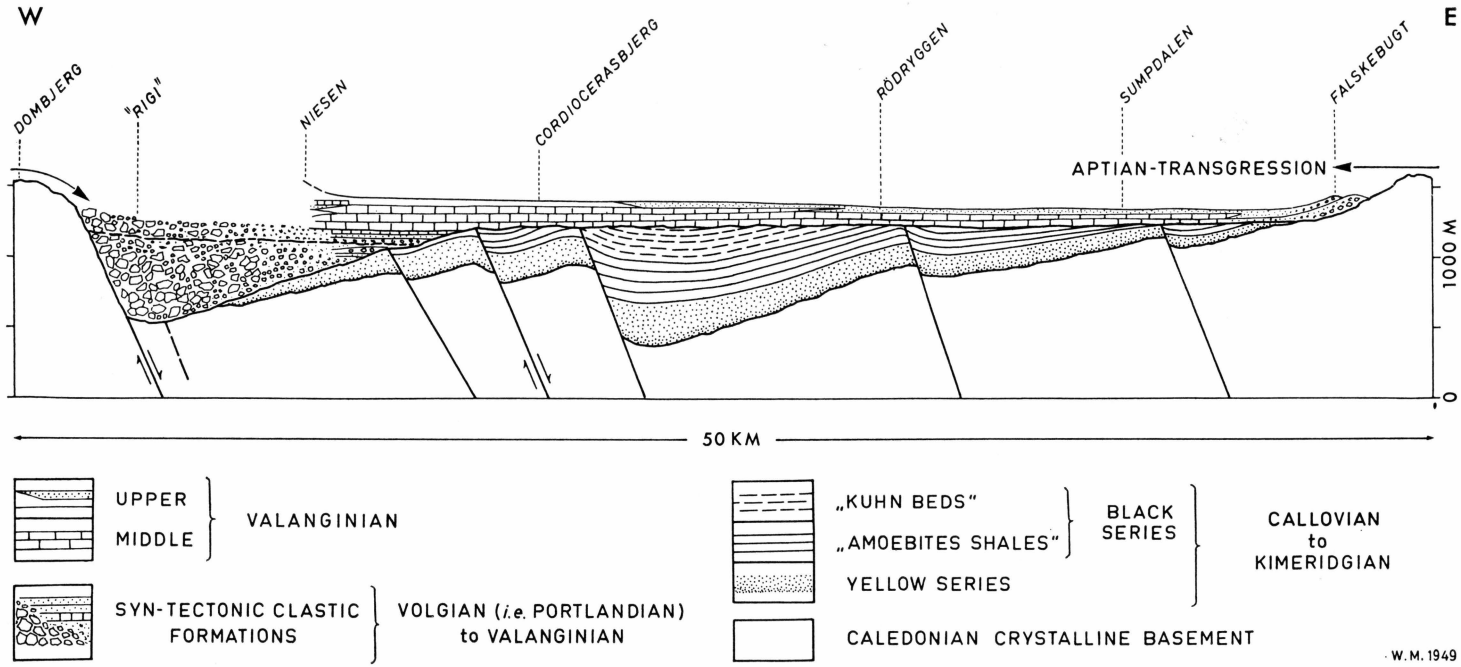


Fig. 71. Diagrammatic section through northern Wollaston Forland showing late Jurassic step faulting and tilted blocks, and facies conditions in Lower Cretaceous cover strata. — After W. Maync (1949, pl. 3).

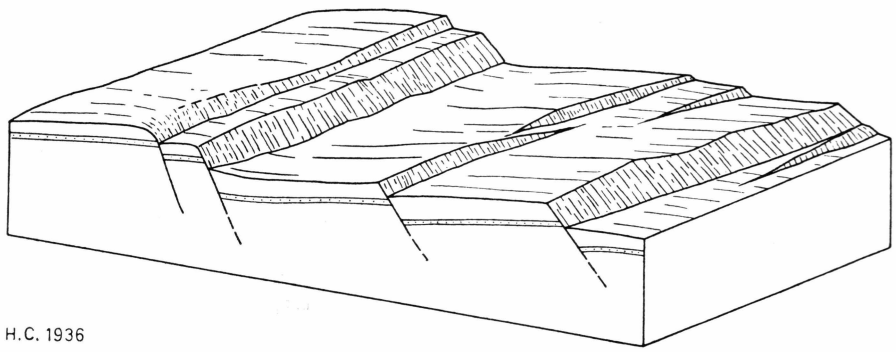


Fig. 72. "*Antithetische Verwerfungstreppe*" (antithetic block-faults *en echelon*). — Adapted from H. CLOOS (1936, p. 268).

The principles of block-fault tectonics developed in the late Jurassic are clearly pictured in the diagrams adapted from W. MAYNC and A. VISCHER (Figs. 70, 71). By studying these diagrams it becomes evident that in late Jurassic times East Greenland's continental border could no longer resist the continuous crustal tension, and block faulting resulted. The initially wide-arched monocline of the continental border gave place now to an entire belt of *en echelon* faults which took up once more the northerly trend of the late Paleozoic pattern of fault blocks. Considerable relief was attained by the new faulting, as the different blocks slipped past each other and at the same time, were tilted westwards. Thus, while the faults dip seawards, the different blocks were rotated towards the stable continent. The upper surface of each block pushed against the fault scarp of the adjacent block to the west. In that way the inclined surface of the one block came to push against the fault scarp of the adjacent western block. This series of tilt-blocks is best designated by H. CLOOS's term "*Antithetische Verwerfungstreppe*" (antithetic[79]) block-faults *en echelon*) shown in Fig. 72.

[79]) H. CLOOS (1928, p. 251): 'Ich verstehe unter *antithetischen Bewegungen* solche kleinere Bewegungen, welche im Gange grösserer, aber in entgegengesetztem Sinne vor sich gehen. Sie treten sowohl im Falten- wie im Bruch- oder Schollenbau auf und erfüllen daselbst die Aufgabe, tektonische Arbeit zu sparen. Und zwar gestatten sie, horizontale Verkürzung (bei Faltung) bzw. horizontale Verlängerung (bei Bruchbildung) unter einem Minimum vertikaler Arbeit auszuführen. Sie sind gewissermassen nivellierende Bewegungen, welche der Herausbildung grosser tektonischer und damit auch morphologischer Höhenunterschiede entgegenwirken und dem Relief eine obere Grenze setzen.'



Fig. 73. Aerial view of southern Kuhn Ø with Fligelys Fjord and Grandjeans Fjord in the background. The photograph clearly depicts an *antithetic fault block* (compare Fig. 72). The rugged hill slopes in the foreground are made up of Caledonian crystalline rocks, *i.e.* gneissified Eleonore Bay beds including some pegmatite dikes (P). Three minor fault (f) run northwest-southeast across the gneiss complex, which is truncated by a conspicuous peneplain surface of early Mesozoic date. This surface was still remarkably level at the time the light-colored sandstones of the Middle Jurassic "Yellow Series" (22) transgressed across the land "Eskimonia" (cf. Figs. 67–69). Coarse-clastic Volgian formations, preserved at the shore of Fligelys Fjord but mainly occurring at Wollaston Forland, indicate a phase of major faulting and block tilting in the Upper Jurassic. This caused Cretaceous and younger formations to overstep and overlap the Middle Jurassic. At the outcrop pictured, however, Cretaceous beds had been entirely removed before basaltic lavas (Z) flooded the area in early Tertiary times so that the angular unconformity between the westerly dipping Middle Jurassic and its horizontal cover is seen at the base of the basalt flows. — Air-phot. F. Schwarzenbach, 1956.

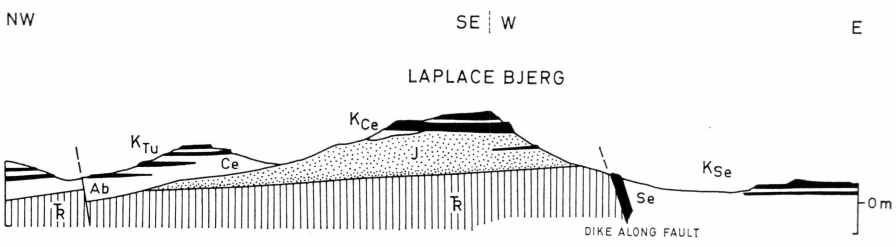


Fig. 74. Structure section through Laplace Bjerg (eastern Geographical Society Ø). T_R = Triassic, J = Jurassic ("Yellow Series"); Cretaceous rocks are shown uncolored: K_{Ab} = Albian, K_{Ce} = Cenomanian, K_{Tu} = Turonian, K_{Se} = Senonian (Upper Campanian). Tertiary basic intrusions are shown in solid black. — After D. T. DONOVAN (1955, p. 45).

On account of the westward tilt of the sedimentary laden fault blocks, the surface traces of the new faults obviously marked tectonic depressions which immediately were flooded by the encroaching sea. The area of "Niesen Fjord", in particular, was the site of such a tectonic groove. In the center of this trough, presented by the section exposed at "Niesen" Mountain, sedimentation was more or less continuous from Volgian into the Valanginian. The western boundary of the basin, of course, remained in the same position during this time, but eastward there was a gradual encroachment of the sea over much of the Wollaston Forland area during the Valanginian, so that in central Wollaston Forland Valanginian rocks rest unconformably on tilted Jurassic sediments.

Subsidence and tilting of fault blocks was apparently most intense in the northern sections of Central East Greenland (Fig. 73). Yet, if it is as assumed by D. T. DONOVAN (1957, p. 97) the main episode of westward tilting of fault blocks in Traill Ø and Geographical Society Ø was contemporaneous to that of the northern region, although in the south the dating is less precise as here the only visible unconformity is revealed by Albian/Cenomanian beds transgressing across tilted early Upper Jurassic strata (Fig. 74).

In the very southeast, in **Milne Land**, the "Kimeridgian Clays" (cf. p. 155) are conformably followed by a series of thin beds in some of which *glauconite* is a major component, while in others shellbanks crowded with fossils occur. These beds, some 80 m in thickness, change rapidly and correlation by lithology is impossible over any distance. L. F. SPATH (1936) compared these remarkably fossiliferous "*Glauconitic Series*" with the uppermost Kimeridgian and the Lower Portlandian (*i.e.* the Portland Sand series of Dorset, England). The glauconitic beds are overlain with slight unconformity by the "*Hartzfjeld Sandstone*",

a 300 m thick series of barren sands and more or less massive sandstones and subsidiary shales, including a number of thin marine beds in the lower part. The base of the succession is made up of a medium to coarse-grained, cross-bedded sandstone, up to 40 m thick. The bulk of the series reveals repetitive cycles of medium to coarse grained sandstone followed by micaceous sandy shale including calcareous and clay ironstone concretions. The majority of fossils, unfortunately from the view point of correlation, are lamellibranchs. In the lowermost marine horizon the rare ammonites are pavlovids and *Laugeites*, known also from Kuhn Ø. The next higher marine beds include ammonite forms very similar to those found in the Russian Upper Ryazan beds and the English Spilsby sandstone, and hence are to be ascribed to the Berriasian (Cretaceous). The uppermost 100 m of the "Hartzfjeld Sandstone" commences with dark micaceous clays, followed again by alternating beds of sandstone and sandy clay. They have yielded no fossils except poor plant remains, and the age of this part is therefore unknown.

The unconformity at the base of the "Hartzfjeld Sandstone" as well as the distinctively cyclic character of this series indicate frequent incursions of the sea and are likely to reflect some oscillating block displacement in the southern section of Central East Greenland, although in Milne Land itself conditions remained rather stable throughout the time of the turn from the Jurassic to the Cretaceous.

The transgression of the Valanginian sea

In Middle Valanginian time marine beds[80]) transgressed over tilted and eroded beds of different age, thus indicating another incursion of the sea after the principal phase of block faulting. In *Store Koldewey Ø*, the Lower Cretaceous sea—as it had done in the Upper Jurassic and was to do again in the Aptian—lapped against the base of a steep coastline which was in much the same position as the present-day east coast of the island. In the *Wollaston Forland* area (cf. Fig. 71) the varied facies of Valanginian beds (marls and marly shales with limestones *versus* coarse clastic beds accumulated near steep coast-lines) evidently reflects the continued existence of some sort of a basin-and-range topography along Greenland's east coast. From the area south of the 74th parallel, however, information is poor. The deposits of early Cretaceous age found in *Traill Ø* cannot at present be fitted into a broader picture. The facies which are present correspond closely to those in Wollaston

[80]) Polyptychitan stage.

Forland, but there is no clue as to the extent of the sea in which they were deposited.

The end of this early Cretaceous inundation is not accurately known. In Wollaston Forland, at the summit of 'Niesen' Mountain, an Upper Valangian ammonite was found and D. T. DONOVAN (1957, p. 112) assumed that still younger beds have been removed from this section by denudation. There is, however, no positive evidence of either Hauterivian or Barremian deposits, as emphasized by W. MAYNC (1949, pp. 193–95) and a regression of the sea during these two stages over all of Central East Greenland is agreed by both MAYNC and DONOVAN. Moreover, the distribution and superposition of the transgressive Aptian/Albian succession suggests a period of profound denudation preceding the widespread incursion of the sea. This refers in particular to Geographical Society Ø and Traill Ø where Upper Jurassic and early Cretaceous beds apparently have been removed almost completely during this period of emergence. Farther north, at Falskebugt (Wollaston Forland) an angular unconformity between Valanginian and Aptian indicates additional displacement and tilting of the coastal blocks.

The Aptian-Cenomanian transgression

The Aptian-Albian coast of East Greenland may be visualized as fringed by islands, striking north and south, still formed, however, by the unsubmerged parts of the tilt blocks of Jurassic and older rocks. As the transgression proceeded these islands shrank, and had vanished early in the Cenomanian, when the sea reached its widest extent. The transgression commenced in *Lower Aptian* time. In spite of the period of erosion that preceded this new incursion of the sea, the invaded country still exhibited a modest relief. Lower Aptian deposits are mainly represented by sandstones, sometimes indistinguishable in lithology from the "Yellow Series" of the Jurassic; they probably derived from the same source and possibly partly from the "Yellow Series" itself which may have been exposed to denudation in places. Lower Aptian beds occur in Hold-with-Hope, Wollaston Forland and Kuhn Ø.

By the *Upper Aptian*, evidently, a much wider area had been invaded by the sea; these beds we find again in Wollaston Forland and on Kuhn Ø, but also on Shannon Ø, Store Koldewey Ø and Germania Land. In the northern region the transgression probably reached its maximum extension at that time although its progress is not traceable in detail. In the southern region, however, in Geographical

Society Ø and Traill Ø, the sea continued to creep up the dipslopes of the tilted blocks during the *Albian* and early *Cenomanian* stages, and it was only during the latter period that the area was completely submerged[81]). The Albian-Cenomanian transgression, ascertainable throughout the Traill Ø region, is apparently the southern extension of the older, Aptian-Albian transgression recognized north of Kejser Franz Josephs Fjord. In the Wollaston Forland area, however, there is no evidence that sedimentation was continued into the Cenomanian although it seems likely that it was.

The western limit of the Middle Cretaceous transgression was formed, in the northern region, by a set of northerly running faults[82]) lying east of the "*post-Devonian main fault*". In Geographical Society Ø and Traill Ø, the "main fault" itself formed the boundary of the depositional area; along the scarp accumulated a belt of sandy marginal wedges interfingering with the normal shaly facies of the Cretaceous. To the west of the fault line Devono-Carboniferous molasse beds and denuded blocks of the Old Caledonian fold belt stood above sea-level. W. Maync concluded that sedimentation was rather rapid in part. The clastic beds show unsorted material and there is frequent evidence of slumping. According to J. Putallaz (1961, p. 78) the Albian-Cenomanian succession exposed in Traill Ø exceeds a total thickness of some 1,200 m. Except for near-coast deposits, however, the Albian and Cenomanian developed mainly in the form of *black shales* with abundant clay-ironstone bands and concretions; in places the shales are punctuated by subsidiary bands of sandstone. The black shale facies may be attributed to deposition in basins isolated by the emergent edges of tilted fault blocks, the same depositional environment postulated for the Upper Jurassic "Black Shales" (cf. p. 154). As there are no sediments of proven Upper Cenomanian or Lower Turonian age in East Greenland, it is assumed that the sea receded from the coastal area during that time.

The transgression of the Upper Cretaceous sea

Upper Cretaceous rocks are very restricted in occurrence. *Turonian* beds have been found only in Traill Ø and Geographical Society Ø; they are best known in the Maanedal area (northeastern part of Traill Ø), where a series of coarse clastic beds is considered to represent the

[81]) D. T. Donovan (1955, p. 54).
[82]) W. Maync (1949, p. 215).

basal conglomerate of the Turonian. Nowhere, however, has the contact between the Turonian and the subjacent beds been seen.

In Traill Ø the western limit of the Upper Turonian conglomerates and associated rocks was apparently the scarp of the "Maanedal fault". Carboniferous and Permian rocks exposed to the west provided the clastics poured into the fault-bounded Turonian sea. Farther from the coast *black shales* accumulated once more. Yet subsidiary bands of sandstones and isolated patches of conglomerate are frequent in this series. It is assumed that the important fault zone of which the "Maanedal fault" was a component also formed the coast of the Turonian sea in Geographical Society Ø and in southern Traill Ø, as it had done in Aptian-Cenomanian times.

North of Kejser Franz Josephs Fjord, no Turonian rocks have been found yet. But certainly in *Santonian* (Senonian) time a marine incursion took place in eastern Hold-with-Hope. At the same time the eastern parts of Geographical Society Ø and Traill Ø were submerged as well. From a few places in these two islands *Upper Campanian* (Senonian) beds are also recorded. Yet it is unknown whether these beds represent a continuation of deposition from the Upper Santonian or a new incursion of the sea. The Senonian transgression is recognized over a large part of East Greenland, since marine Senonian formations also form the lower part of the *Kangerdlugssuaq Sedimentary Series*, which crops out below the Tertiary plateau basalts in the country south and east of the inlet Kangerdlugssuaq, between 68° and 69° N (cf. p. 190). Here, the Upper Cretaceous transgressed across the Precambrian basement complex. A similar and perhaps contemporaneous marine transgression took place farther south on what is now Kap Gustav Holm (66°30′ N).

The development of East Greenland's Mesozoic seaboard

From D. T. DONOVAN's comprehensive paper of 1957 it becomes evident that from Scoresby Sund northward, at least as far as Store Koldewey Ø, the Jurassic and Cretaceous coastlines lay approximately parallel to the existing coast. During times of marine transgressions the shore lay to the west of the present outer coast, during regressions it may have lain to the east. But apart from these matters of detail, the relationship of land and sea was the same during Mesozoic time as it is today.

The structure of East Greenland's Mesozoic seaboard has been shown to consist of tilted and faulted blocks. According to A. VISCHER (1943) *the locus of faulting shifted successively eastward during Mesozoic time.* This tendency had already been established for Paleozoic fault

systems. Apart from minor fault patterns[83]) showing a west-to-east sequence, two major lines strikingly reveal the eastward shift of fault tectonics, that is the "*Kong Wilhelm's line*" traceable from Nordfjord (74° N) to Germania Land (77° N), followed—some 70 km farther to the east—by the "*post-Devonian main fault*" running from Scoresby Sund north through the whole of Central East Greenland. The first of these fault lines was the site of considerable and repetitive displacement from Lower(?) to early Upper Devonian times (cf. p. 101). The "*post-Devonian main fault*" came into being in Carboniferous times (cf. p. 137), but remained an active element throughout Mesozoic and Cenozoic times. The area east of the "main fault" acted largely as a coherent block, which gave rise, south of the 74th parallel, to a north-south basin structure in the Triassic and Liassic (cf. Fig. 68).

By late Middle Jurassic time a major incursion of the sea established a maritime regime over most of the coastal area of Central East Greenland, from Scoresby Sund (70° N) to Germania Land (77° N). At that time of submergence the simply built coastal block began to differentiate into compound structures of smaller magnitude although the depositional environments still developed fairly uniformly (*viz.* the "Yellow" and "Black Series" of Callovian and Oxfordian/Kimeridgian age respectively). Finally, decisive decomposition of the coastal block occurred at the close of the Jurassic time, when numerous further fault lines running NNE–SSW, *i.e.* parallel to the "main fault", but also of NNW–SSE strike came into being. A. VISCHER concluded that most of these subsidiary fracture systems were largely synchronous, as they do not intersect but relieve one another. Owing to the divergence between the north-north-easterly running "post-Devonian main fault" and the generally northern trend of the present coast the outcrop area of Mesozoic beds grows smaller and smaller from south to north.

A. VISCHER's sequential sections showing the post-Caledonian block faulting in the region between 74° and 75° N clearly depict the gradual development of an *antithetic block fault system* (cf. Fig. 70). The unconformable superposition of successively younger sedimentary formations indicates repeated displacement along the major fractures. The tilt blocks slope towards the continent, the fault planes hade towards the sea. The geometry of this breakage scheme reveals a predominance of *tensional effects*, for a considerable amount of apparent vertical displacement turns out to be caused by antithetic rotation[84]). In a short note

[83]) For the late Caledonian fracture patterns in Andrées Land, E. FRÄNKL (1953 a) and J. HALLER (1953) have shown that the oldest fault lies in the west, the youngest in the east; H. R. KATZ (1952 a) found the same relationship in Strindbergs Land.

[84]) "*Antithetische Rotation*", cf. H. CLOOS (1939, pp. 424–28).

on the tectonics of East Greenland's coast, H. CLOOS (1940) discussed to what extent VISCHER's tensional breakage scheme involved relative vertical displacement (throw) as well. With reference to fault patterns exposed along the margins of well-known graben structures he concluded that the East Greenland scheme reflects a crustal widening closely related to a 'vertical displacement of higher order'. CLOOS (*op. cit.* p. 180) meant by this a gravitational lateral movement of crustal material from a stable highground to an unstable sinking area[85]). We thus arrive at the concept of a large-scale destruction and break-down of former Caledonian land-masses along the northerly trending fracture pattern. This process was more or less continuous; it began in the late Paleozoic and reached its climax evidently in the latest Jurassic—at a time incidently when much tectonic unrest occurred also along the western flank of the Laurentian block (Nevadan orogeny). The subsided tracts of the East Greenland Caledonides gradually became part of the Scandic Sea.

E. FRÄNKL (1956, pp. 39–40) called attention to the time pattern of Mesozoic marine incursions traceable along the north-south axis of the decomposed East Greenland fold belt. He concluded that a gradual subsidence of the 'Scandic block' took place progressively from north to south. Admittedly, FRÄNKL's concept of a southward expansion of the Arctic maritime realm across the Scandic region[86]) is deduced from East Greenland stratigraphy, and with regard to the whole region it might be oversimplified. It is, however, in agreement with W. J. ARKELL's conclusion that the lay-out of the world's 'Jurassic stratigraphy requires the existence in Jurassic times of the North Pacific, *North Atlantic*, *Scandic* and *Arctic Oceans*' (1956, p. 605). There is evidence that the Scandic Sea came gradually into existence through late Paleozoic[87])

[85]) H. CLOOS' term of "*Vertikalverlagerung höherer Ordnung*" might well be translated nowadays in terms of 'mantle tectonics'.

[86]) Designated as "*Thulean Basin*" by R. W. VAN BEMMELEN (1965); the use of the term "*Thule*", however, should be restricted to Precambrian geology, see p. 48.

[87]) It was suggested by T. J. WESTOLL (1965, p. 22) that the initial post-Caledonian 'opening' of the Scandic basin dates back to Devonian times. Yet, his argument is essentially focused on the age of displacement along the *Great Glen Fault*. As he says, 'The first fractures foreshadowing the present North Atlantic seem to have developed between the Lower and Middle Old Red Sandstone; the Greenland-Norway fracture seems to have split southwards, one branch between southeast Greenland and the continental margin northwest of Scotland, a second forming the Great Glen fault (possibly continuous into the Cabot fault of Newfoundland), and a third curving branch along the Skagerrak. The main sinistral transcurrent movement along the Great Glen fault (about 100 km) can be dated on very

and Mesozoic times by successive rifting and breaking-down of Caledonian land masses resulting in various submerged basins. Moreover, as a speculation it is suggested that East Greenland's major tensional fracture system of late Jurassic date largely coincides with the initial formation of the Mid-Atlantic Ridge.

The concept of a southward expansion of the Arctic Sea through late Paleozoic and Mesozoic times will probably be opposed by the believers in the giant Atlantic jigsaw puzzle, who, matching present-day fathom lines on both sides of the Atlantic, postulate a coherent block ('*Pangaea*'[88]) that cracked from south to north and drifted apart in the late Mosozoic. Ever since the early 17th century, when the philosopher FRANCIS BACON drew attention to the parallelism of the opposing shores of the Atlantic, this striking feature has been a stimulus to discussion among geologists. Certainly, the morphological fit[89,90]) of the old and new hemispheres is significant and through the trick of a magician[91]) it became even perfect. Last but not least the manually juggled fit was confirmed by Cambridge University's computer EDSAC 2 when it was fed with 500 fathom contours of the continental slopes of North America, Greenland, and Europe (E. BULLARD *et al.*, 1965).

Yet a theory is a tool—not a creed. I am aware, however, that to many geologists continental drift—for several reasons—has become a "logical necessity" and hence a creed and axiom. If I add here critical

reasonable stratigraphical evidence as post-Lower, pre-Middle Old Red Sandstone. Such movement can hardly have occurred without opening a rhombochasm farther north between north Norway and Greenland; it is not possible to date other early movements so clearly, but it is remarkable that in belts along the lines of the fracture system there is a wholly individual development of non-marine sediments of Middle and Upper Devonian age with a considerable faunal community. Throughout the Carboniferous most of this system of rift-like depressions, and erosional depressions along the lines of fracture seems to have been the site of essentially continental sedimentation, with only slight marine invasions. By Upper Permian times, however, the depressions were deeply invaded by marine transgression from the north, which spread over large tracts of northwest Europe and gave rise to broad nearly land-locked seas, in which vast quantities of evaporites were deposited, communicating with open waters northwards only via the Greenland-Norway rhombochasm.'

[88]) For the compressed combination of Laurasia and Gondwana the name '*Pangaea*' was proposed by A. WEGENER (1924).

[89]) ... 'Die erste Idee der Kontinentalverschiebung kam mir bereits im Jahre 1910 bei der Betrachtung der Weltkarte unter dem unmittelbaren Eindruck von der *Kongruenz der atlantischen Küsten*, ich hielt sie aber zunächst unbeachtet, weil ich sie für unwahrscheinlich hielt' ... (A. WEGENER, 1922, p. 3).

[90]) ... 'if the fit between South America and Africa is not genetic, surely it is a device of Satan for our frustration ...' (C. R. LONGWELL, 1958, p. 10).

[91]) S. W. CAREY (1958 a).

comments I admit to scepticism toward drift hypotheses, but this should not suggest, by any means, that I am advocating J. D. DANA's concept of the permanency of continents and oceans, neither in the sense of their geographic position nor in the sense of their lithogenic immutability. A review of the pros and cons of the numerous theories that let Greenland (as part of the Laurentian block) wander about relative to Eurasia is beyond the scope of these comments. Each of these hypotheses has its own preferred solution of the puzzle in the North Atlantic and Scandic. With some rare exceptions, however, they all agree that the decisive events occurred in the latest phase of the earth's history, and that the rift along the Atlantic advanced northwards[92]) so that the Laurentian block became separated from Eurasia only in the Tertiary, and Greenland drifted westwards[93]) only very recently.

[92]) A. WEGENER (1924, p. 42) says, 'The Atlantic rift is broadest in the south, where it first broke open. Its width amounts here to 6,220 km. Between Cape San Roque and the Cameroons there are 4,880 km., between Newfoundland Bank and the British shelf 2,410 km., between *Scoresby Sound* and Hammerfest but 1,300 km, and between the margins of the shelves of *North-East Greenland* and Spitsbergen probably only from 200 to 300 km. Here the split appears to have taken place in quite recent times'.

[93]) Concerned with objections against his concept, ALFRED WEGENER pointed out that 'the hypothesis of continental drift has one advantage over all other geological theories, that it involves the possibility of *checking its truth by repeated astronomical observations of latitude and longitude*' (A. WEGENER, 1928, p. 100). Some ten years later his brother KURT was able to present the clue to this truth by stating: 'Anderseits hat sich rezent aus den astronomischen Beobachtungen in Grönland in voller Klarheit gezeigt, dass Grönland sich mit einer geradezu unglaublichen Geschwindigkeit im Laufe der letzten 100 Jahre bewegt hat.' (K. WEGENER, 1939, p. 4). In the scope of my review I feel that this is the appropriate place to emphasize that the often claimed westward drift of Greenland is nothing but a marathon of errors.

Repeated determinations of geographic coordinates were made on both sides of Greenland, namely on the east coast at *Sabine Ø* (74°36′ N) and at the west coast at *Qôrnoq* (64°32′ N). The first recorded observations at the east coast were made by Cpt. E. SABINE in 1823 (cf. p. 20). BÖRGEN and COPELAND failed to identify the site of SABINE's observation when in 1870 they arrived on SABINE's "Pendulum Islands" with KOLDEWEY's expedition (see J. P. KOCH, 1916, pp. 240–56). They made determinations of latitude and longitude on a point which they believed to be within 100 meters of SABINE's location, but the admitted uncertainty makes any comparison with SABINE's results valueless for scientific use.

In 1907, using his observatory at *Danmarkshavn* (76°50′ N) as a base, J. P. KOCH ran a triangulation net southward to include the 310 m high coast mountain *Haystack* (75°44′ N). This point, although crucial to the following conclusion, admittedly was never marked off by a cairn. Yet, as indicated by its name (coined by Cpt. CLAVERING in 1823) the top is shaped like a regular cone so that it was used as geodetic sighting-point both from the south by the German surveyors and from the north by J. P. KOCH. The computed values of the latitude of Haystack harmonized better than expected, the difference being some 120 meters. J. P. KOCH's de-

All aim at an explanation of how the salient "*chasms*"[94]) of the earth's face were brought about, that is to say, the theory presents a

termination of the longitude, however, indicated the position of Haystack as 2'36" or some 1,190 meters more westerly than the determination of 1870 (J. P. Koch 1916, p. 240). These figures—focusing on the misfit or two independently established triangulation nets at their mutual sighting-point *Haystack*—were henceforth cited as evidence that Greenland moved westward at an average yearly drift of 32 meters (*op. cit.* p. 246).

In 1932, H. S. Jelstrup reoccupied the exact site of the observatory used by the Germans in 1870. He was the first to employ radio time-signals on *Sabine Ø*. Yet in his conclusions he fully approved the determination made in 1870—longitudinal values based on lunar culminations and star occultations—and obtained thus for the 62-year interval a westward shift of Sabine Ø of 615 meters (Jelstrup, 1933, p. 25). Since J. P. Koch's results have been cited by advocates of the continental drift hypothesis as equally reliable and hence valid in evidence it would be necessary to conclude that Sabine Ø station moved westward 1,190 meters between 1870 and 1907, and retreated eastward 575 meters in the 25 years following 1907. With this, 'the layman in such matters is left with an uncomfortable feeling . . .' sights Yale's structural geologist C. R. Longwell (1944 b, p. 404) reviewing the credibility of Greenland's shifting coordinates.

Nevertheless, it was argued that the measure of westward shift indicated by the East Greenland results was much larger than the probable error of the method. Moreover, the east coast data received strong support through the fact that in the twenties consistent results were obtained at the west coast station *Qôrnoq*. Observations to determine the position of this location at Godthaab Fjord were first made in 1863. Twenty years later the station was reoccupied and found to lie over 400 meters *east* of the position reported earlier. In 1922, P. F. Jensen, using radio time-signals for his determination, calculated a position farther west. He averaged the two earlier results (made on the basis of lunar culminations) to a hypothetical position of 1873 and obtained from this on a 49-year basis a westward shift of 20.2 meters per year (Jensen, 1923, pp. 274–75, 283). In 1927, the Danish Geodetic Institute again occupied the station, and announced a value about 180 meters west of Jensen's. Both A. Wegener (1929, pp. 27–29) and A. du Toit (1937, p. 300) hailed these results as a quantitative demonstration that Greenland is moving west at an annual rate of about 36 meters. The Geodetic Institute, however, repeated the observations in 1936, and obtained a longitudinal value essentially identical with that of 1927. N. E. Nörlund (1937, pp. 505–06) the Institute's director, therefore, included the value of 1922 among the older unreliable observations and listed the operation of 1927 as the first to give a dependable result. At that time also a concrete pier was established at Qôrnoq and subsequent measurements in 1936 and 1948 resulted in essentially identical values. The slight difference of $0^s.02$ between the value obtained in 1927 and that of 1948 was attributed to personal equation in the "Geodætisk Institut Skrifter" by E. Sinding (1955, p. 11).

Longitude observations made in *Jan Mayen* have been reviewed by G. W. Tyrrell (1935).

[94]) S. W. Carey (1958 a, pp. 192–93) distinguished between: "*Rhombochasm*", a parallel-sided gap in the sialic crust occupied by simatic crust and interpreted as dilatation, and "*Sphenochasm*", a triangular gap of oceanic crust separating two cratonic blocks with fault margins converging to a point, interpreted as having originated by the rotation of one of the blocks with respect to the other.

mechanism that would accurately roll up and close the Atlantic gap. As it was in the past, so temptation will remain for forthcoming speculators to base their restoration of former super-continents and mountain connections solely on the present-day physiography of sea and land areas. Restoration, however, is in the first place a matter of history[95])[96]). It is through a retrospect in space and time that we have to find out about the grade of completeness and the magnitude of a particular structure belt exposed on the continent. Unfortunately it had too often been a paralogism of geologic concepts, especially of structural synthesis, to correlate what looks apparently similar. A very recent statement[97]) matches without hesitation the "Moine Thrust" of Scotland with the frontal thrust system of the East Greenland Caledonides exposed in inner Scoresby Sund (cf. p. 47) forming a 'geotectonic lineament'[98]). False conclusions of this sort are frequent. I should like to recall at this place another example, that is the nappe tectonics of the Alps. To the explorers of the Alpine structure it took quite a time to realize that a nappe unit and its 'root zone' together only form an entity that is made up of *complementary parts*—not of similar parts. In the same way, I think, by discussing former connections of the old and new hemispheres we first have to realize that on both sides of the Atlantic important and sizeable parts of the Paleozoic and Precambrian structure belts have disappeared. Thus the Caledonian belts surrounding the Scandic Sea merely represent the mutilated remnants of a widely ramifying mountain system in the Paleozoic. To each of these maimed limbs, of which the East Greenland fold belt is one, considerable complementary areas have to be considered (cf. C. E. WEGMANN, 1948, p. 30–35).

Although the bathymetry of the ocean basins may well picture tectonic features that came into being during the process of down-breaking

[95]) '... the whole trouble in WEGENER's hypothesis and in his methods is ... that he generalizes too easily from other generalizations, and that he pays little or no attention to *historical geology* or to the time of the making of the structural and biologic phenomena discussed. It is not, as he says, that the detailed worker cannot see the forest because of the many different trees, or that the paleontologists need a geophysicist to show them the road on which they should travel. Facts are facts, and it is from facts that we make our generalizations, from the little to the great, and it is wrong for a stranger to the facts he handles to generalize from them to other generalizations.' (C. SCHUCHERT, 1928, p. 139).

[96]) 'Clearly, a great deal of work needs to be done before we can fully accept the hypothesis that the Atlantic Ocean was formed by continental fragmentation ... Some of the most important data bearing on it will probably come from detailed *comparative geological studies* of geometrically matching areas that have structures truncated at the continental margin, particularly where this is narrow'. (E. BULLARD *et al.*, 1965, p. 50).

[97]) L. R. WAGER, and E. I. HAMILTON (1964).

[98]) R. W. VAN BEMMELEN (1965, p. 412).

of the truncated Paleozoic mountain system, neither the relief of the sea floor nor that of the adjacent land reflect an outline of Caledonian tectonics. With reference to the morpho-genetic featuring of the recent mountain ranges in both North and East Greenland I pointed out (p. 27) that both were brought about by differential displacement of the Paleozoic truncation plane in Mesozoic and Cenozoic times. It is true that the structural framework of the Paleozoic fold belts partly guided the trend of younger block-fault tectonics, but nevertheless *the present physiography of East Greenland and its continental margin is essentially a reflection of an independent post-Caledonian history.* In Northeast Greenland the 'Caledonian' drama ended in Carboniferous time and in Central East Greenland it came definitely to its end when the Upper Permian sea transgressed across the bevelled land. In Mesozoic and Cenozoic time, similarly, all the truncated Paleozoic belts bordering the North Atlantic underwent epeirogenic distortion which in principle was independent from the structural make-up of these former mountain belts. A superb example of this independence is the deformation of the fall-line surface of the Appalachians as strikingly pointed out by M. P. Billings (1960).

In discussing the development of East Greenland's Mesozoic seaboard we have to deal particularly with large-scale geomorphological features that characterize the *late history* of continental masses all over the globe. The significance of such studies was demonstrated by L. C. King (1950, 1962) and their general aspect is probably best summarized by the words of E. S. Hollingworth[99]), who commented: 'The fact that the greater part of the earth's land areas have been almost 'dead' structurally for much of Mesozoic and Tertiary times is sometimes overlooked by structural geologists absorbed in orogenic problems. In these masses epeirogenetic movements, with some faulting and gentle warping, have in general dominated the scene. The fact that movements have been mainly positive implies that the later history of the continents is necessarily largely based on *denudation chronology* dated by evidence of marginal transgressions.' Much important information on the history of the ocean basins, particularly the Atlantic, indeed, is being obtained from 'denudation chronology'. With regard to this it is essential to note that to both sides of the North Atlantic the major reference plane, that is the Paleozoic base upon which the pile of Mesozoic and Cenozoic coastal plain and shelf deposits accumulated, was found to slope considerably towards the ocean basin. Examples are quoted from the European shelf off the English Channel, where the basement of crystalline rocks warps steadily downwards to a depth of some 2,400 m at the

[99]) E. S. Hollingworth (1950) *in discussion* (L. C. King, 1950), Quart. J. Geol. Soc. **106**, p. 130 (London).

outer edge of the shelf. The same feature was found at the shore of Africa. Complementary sections were obtained by geophysical and drilling studies from the Atlantic shelf along the United States, where the pre-Jurassic surface of subaerial erosion is now buried, more than 3,000 m, beneath the shelf deposits. Analogous displacements of the pre-Upper Permian surface have to be assumed for the shelf of Northeast Greenland. Along the coast of Central East Greenland, however, partly *exhumed by Cenozoic uplift and erosion, a great part of the Mesozoic structural history is revealed* in the present outcrop pattern and is thus accessible to field-geological methods and argumentation.

7. CENOZOIC DISTURBANCES AND IGNEOUS ACTIVITY

The turn from the Mesozoic to the Cenozoic brought a drastic change and a novel element into the post-Caledonian history of East Greenland which then became the site of intense igneous activity. This caused the building up of basaltic plateau accumulations of enormous size; ultrabasic to acid differentiates of the associated magma were emplaced in a row of plutonic centers, and widespread intrusions of dolerite dikes and sills occurred. Tertiary formations, predominantly igneous rocks but including minor occurrences of sediments as well, are distributed over considerable parts of East Greenland, from Kangerdlugssuaq (68° N) to Shannon Ø (75°30′ N), mainly along the coastal area (cf. Fig. 3).

The East Greenland igneous region, some 900 km in length, is only part of the vast field of early Tertiary volcanicity stretching across the North Atlantic and known as the "**Brito-Arctic province**"[100]). The NW–SE trending major belt includes the Tertiary igneous region of Scotland and Ireland, the Faeroes, Iceland, and both East and West Greenland. In his compilation of 1918, A. HOLMES considered also Jan Mayen, Spitsbergen and Franz Joseph Land as associated parts of the province. Modern volcanism, however, is confined to Iceland and Jan

[100]) When A. HOLMES in 1918 introduced the term "*Brito-Arctic province*" he explained his concept of 'petrographic provinces' which includes petrologic as well as geotectonic aspects. An ideal province, he said, 'demands that similar rocks belonging to similar series (defined by their range of chemical and mineral composition and textures) must be produced in adjacent centres of igneous activity during the same period. This implies that the processes by which the rocks are formed must be similar throughout the province, and that the distribution of rock materials in depth, on which the processes act, must also be similar. One condition alone satisfies these requirements, namely, that all the parts of the province have had a parallel geological history, as regards denudation and sedimentation, earth movements and former periods of igneous activity'. He further commented on the physical behavior of the crustal segment involved, stating (*l.c.*) that 'both denudation and sedimentation affect the distribution of temperature and pressure in depth', and stressing the point that 'earth movements according as they compress or stretch the rocks, inhibit or promote fusion, respectively, so that compression allows fusion to begin only at much greater depths than tension.' (*Op.cit.*, pp. 218–19).

Mayen (the latter consisting of the most northerly active volcano). The The Scoto-Irish region is presumably one of the most minutely mapped and closely investigated igneous fields in the world. Its investigation has resulted in new concepts of igneous intrusions, such as ring-dikes, cone-sheets, and composite sills and dikes. It is noteworthy that the field aspects and the geological significance of the North Atlantic basalt province was better known to the geologists of the last century than to modern workers because of the stimulation of Sir A. GEIKIE's admirable monograph on the volcano-tectonic features of the British Isles[101]). Our generation, however, is priviledged to obtain numerical data on the nature and structure of the earth crust which carries this volcanic load. Yet with regard to our approach by geophysical methods, we have to keep in mind that geological facts, in their strict sense, are those that can be deduced and interpreted from the visible rock material and its structural setting. Seismic, gravimetric, and magnetic data are obtained in terms of physical properties of whole crustal complexes. Although these data are quantitative and factual they still need to be 'translated' in terms of petrology, stratigraphy and tectonics.

A. Geotectonic Aspects of the Brito-Arctic Eruptive Field

The Tertiary history of East Greenland cannot be considered in its regional scope only; it has to be discussed under the aspects of geotectonics. The enormous outpouring of basaltic lava all over the Brito-Icelandic-Greenlandic major belt, some 3,000 km in length, represents a fundamental *novum* to the structural evolution of this part of the crust. The outline of the belt is intercontinental, and on the adjoining continents is runs right across older tectonic units. The making of the entire eruptive field must thus be considered as a manifestation of deep-seated magma resources and mantle tectonics to both of which the affected crust could accomodate itself only in a fairly passive manner.

R. A. SONDER (1938) called attention to the North Atlantic volcano-tectonic NW–SE axis. While reading rhegmatic lineaments on the face of the earth he drew a conceptual line, called the "*Iceland-Red Sea zonal*". This joins on the European mainland the remodelled southwestern flank of the Fennosarmatian[102]) block; it further hits the volcanic field of the Aegean Sea, and south of the Mediterranean Sea, eventually it runs into

[101]) Sir A. GEIKIE (1897).

[102]) *Fennosarmatia*—a term introduced by H. STILLE—is the central stable block of the European continent that includes the Baltic and Ukrainian Shields and the Russian Platform (Sarmatia).

the Red Sea rift system. We shall not investigate the validity of SONDER's magic line. Yet, a review of East African tectonics will be a helpful link to the understanding of the geotectonic setting of the Brito-Arctic province.

East Africa – the features of a continental rise.

Concerned as we are with the geological setting of the Brito-Arctic igneous field, we should perhaps not argue what happened at that time in Africa. We have to visualize that the area in between, *i.e.* southern Europe and the Mediterranean, was the scene of a mighty orogenic activity which created the great Alpine-Himalayan mountain chains. Thus, a lateral link between the field of the Brito-Arctic lava floods and the East African rift system is unlikely. As to their Cenozoic history, however, the two regions have very much in common, that is in the sequence of events which the title of an essay of 1939 by H. CLOOS enumerated: uplift – fracturing – volcanism[103]). This paper deals with the geometrical analysis of some megastructures of the earth's crust, mainly with East Africa and its Tertiary[104]) rift system. The favored mechanism considered to account for the formation of the East African rift valleys is that the principal horizontal stress was one of *tension*[105]) accompanied by gravitational downdropping and tilting of the narrow central fault block. Another mechanism that has been considered too is that the primary stress has been one of *compression*[106]) resulting in reverse faults which have forced the central block downward. All the geological evidence[107]), however, favors a tensional mechanism

[103]) '*Hebung – Spaltung – Vulkanismus*', Elemente einer geometrischen Analyse irdischer Grossformen, (Geol. Rundschau **30**).

[104]) In East Africa, apparently some fractures initiated as early as Middle Jurassic, but major faulting occurred only in Eocene and Miocene times; younger movements were found to be of late Pliocene to early Pleistocene age.

[105]) *Tensional mechanism* was postulated by J. W. GREGORY (1920) Geogr. J. **56**, pp. 13–47, (London); E. KRENKEL (1924) Geol. Rundschau **14**, pp. 209–32, (Berlin); H. CLOOS (1932) Centralbl. Min. Geol., Abt. B, pp. 273–86, (Stuttgart); R. R. WHEELER (1959) Bull. Geol. Soc. Am. **70**, pp. 667–68, (New York).

[106]) *Compressional mechanism* has been suggested by E. J. WAYLAND (1921) Geogr. J. **58**, pp. 344–59, (London); B. WILLIS (1928) Bull. Geol. Soc. Am. **39**, pp. 490–542, (New York); E. C. BULLARD (1936) Phil. Trans. Roy. Soc. **235** A, pp. 445–531, (London); R. B. MCCONNELL (1951) Int. Geol. Congr. 18th Sess, Rep. Pt. 14, pp. 199–207 (London). BULLARD, however, who in 1936 offered a compressional hypothesis to explain the negative gravity anomalies over the rifts, has now abandoned compression in favor of tension (see B. C. HEEZEN and M. EWING, 1961, p. 627).

[107]) A. N. HUNTER *et al.* (1965). Report on the geology and geophysics of the East African rift system (UNESCO/I.U.G.G.) East African Committee for Cooperation in Geophysics, April 1965, (Nairobi). F. DIXEY *et al.* (1965). Report of the Upper Mantle committee UNESCO Seminar on the East African rift system, April 12–17, 1965, (Nairobi).

for the African and Middle East rift systems. This includes the facts that the subsidiary border faults are typically normal, that the plan of grabens is commonly one of zig-zag rectilinear fracturing, and that there is a general lack of folding in any associated rocks. Special attention has been called to the regional setting of the rifts located centrally within the broadly upwarped *Nubian-Arabian Shield* for here a tensional origin is strongly suggested. The scale of this megastructure CLOOS estimated tentatively at 3,000–3,500 km for the diameter of the shield, 4–8 km for the height of the elevated crestal portion, and 1–2 km for the total amount of tensional effects (1939, p. 444). In experimental reproductions he furthermore showed how oblong clay cakes when updomed will form a major graben along their axis but bifurcations at their ends. That graben structures of this type ordinarily branch off is considered to support once more their tensional origin.

In the Nubian-Arabian shield region, volcanic activity set in at the turn of the Cretaceous to the Tertiary, *i.e.* at the beginning of the process of rise and disruption. Vast masses of flood basalts poured out somewhat eccentrically from the intersection of the Red Sea rift with the trench of the Gulf of Aden, which is mainly in Central Ethiopia. With updoming and fracturing in progress considerable lava piles accumulated also on the Arabian flank of the shield. H. CLOOS (*op. cit.* p. 443) pointed out that here, as elsewhere, volcanism and graben faulting were going to share the affected area so that the two largest rift structures did not incubate much volcanic extrusion whereas immense volumes of lava were derived from small graben structures or even from zones merely fractured without noticeable displacement.

The East African rift systems are the largest comparable structures on land. H. CLOOS (*op. cit.* p. 445) assumed that the tensional structures in the form of rifts were essentially controlled by the magnitude of the arching of the shield. He distinctly denied (*l.c.*) any autonomous lateral displacement of the fault blocks on either side of the Nubian-Arabian shield. He saw these rift systems embraced in the entity of the updomed complex and refused to interpret the African rifts as a stage of the beginning pulling apart (drifting) of the continent. However, in their recent studies on seismic refraction, gravity and magnetic anomalies in the Red Sea, C. L. DRAKE and R. W. GIRDLER (1964) reached the conclusion that this rift system results not only from crustal tension (in the sense described by H. CLOOS) but is likely also to be associated with a 'rotational movement of Arabia relative to Africa by some 6 to 9°' (*op. cit.* p. 490). Supporting evidence of this interpretation comes from the relationship of the gravity and magnetic anomalies to the topography of the Red Sea's axial rift trough. The latter conspicuously increases in width towards the south and its large magnetic anomalies are 'almost certainly

due to basic, igneous rocks partly filling a fracture zone'. This and 'the sinuous shorelines suggest a tearing apart of the continental crust' (*l. c.*). Along the axis of the Gulf of Aden a corresponding region of large magnetic anomalies widens towards the east in a way consistent with the suggested *crustal separation*[108]) in the Red Sea.

Transient features of oceanic rises

Though an early Tertiary rise that has much in common with the Nubian-Arabian shield, the Brito-Arctic igneous field is an intercontinental element which is tied up to both sides of the North Atlantic, to Greenland and the British Isles alike. From the center of this Atlantic field of flood basalts emerges Iceland, which is said to represent the crest of the *Mid-Atlantic Ridge*. The geologic setting of the Brito-Arctic province has thus also to be considered from the view point of marine geology and geophysics.

Rise – fracturing – volcanism, that is the order of events found where continental masses were subjected to Cenozoic arching and rifting. According to H. W. MENARD (1965) this order seems to be equally true also for the evolution of oceanic rises. These are enormous submarine mountain systems which commonly lie in the center of ocean basins. However, if their overall distribution is considered they would be more accurately described as encircling continental blocks than as centered in ocean basins. Although the continuity of this world-wide oceanic rise-ridge system was suggested only a decade ago[109]), the general outline of these megastructures has been accurately explored since then. Minor branches of the system are still being discovered and the mere physiographic study of these belts, some 50,000 kilometers long, is by far not completed. Yet at present enough data are at hand to draw some general conclusions on their geophysical characteristics and geotectonic significance. In two regions geologically well explored, *i.e.* along the west coast of the United States and in the Gulf of Aden, oceanic rises even overlap and interfere with continental features. In the latter region the *Carlsberg Rise* of the Indian Ocean joins the East African rift system

[108]) According to A. HOLMES (1965, p. 1078) the term *crustal separation* is used 'to convey the idea of drifting apart without the relative subsidence of a wedge-shaped rift-block. Such separation implies the widening of a crustal fissure into a chasm too vast to remain unoccupied. Sedimentation from the surface could do very little, whereas upward rheid flow from the mantle would be an inevitable consequence of the relief of pressure at the bottom of the growing fissure. One would therefore expect the gap to be self-healing by the gradual introduction of basic material from the mantle: mainly hot mobile rock with molten threads and pockets that ascended more rapidly from depths where the temperatures were higher.'

[109]) M. EWING and B. C. HEEZEN (1956).

discussed above. In western North America, the *East Pacific Rise* trends into the Gulf of California; its crest reappears at sea off northern California and enters the continent once more through a rift in Alaska (Lynn Canal). In California, the Eastern Pacific segment joins the San Andreas Fault, which displays in the form of an *en echelon* pattern of Cenozoic major faults, a remarkable dextral slippage. Thus in this region there is evidence of crustal displacement in the strike direction of the rise rather than tension at right angles to the rise axis as suggested for the African rift pattern. However, from studies of magnetic anomalies in the eastern Pacific, there is further evidence of displacement along east-west fracture belts[110]), that is transverse to the trend of the oceanic rise. Similar transverse fractures have also been mapped along the *Mid-Atlantic Ridge*, namely in the equatorial Atlantic, where some were found to be seismically active. Although only modest parts are known in detail from the worldwide system of oceanic rises, the occurrence of *transverse offsets* of the crestal province seems to rank among the general characteristics. According to MENARD (*op. cit.*, p. 362) further features common to rises are *high heat flow*, *seismicity*, and *rifting* along the axis of the crest belt.

The *Mid-Atlantic Ridge*, that portion of the oceanic rise-ridge system lying in the Atlantic Ocean is the best known portion of the giant feature. Bathymetric profiles[111]) across the Mid-Atlantic Ridge closely resemble

[110]) From north to south these are the *Mendocino* (with the *Pioneer* fracture zone?), *Murray*, *Clarion*, *Clipperton*, and *Carnegie* fracture zones, narrow ridges a few hundred kilometers wide, very straight, and several thousands of kilometers long. They separate gently sloping blocks of the ocean floor of different depths. The eastern ends of these ridges cannot be followed as fracture zones cutting into the continent, but some of them can be connected in other ways to well-known features. The Mendocino fracture, an apparently sinistral system, intersects with the dextral San Andreas fault just at the continental slope. (The pattern of movement along these two closely related master fractures is in essential agreement with the concept of arc-shaped "*abyssal fracture zones*" set forth by G. D. ASHGIREI, 1962, Geologie **11**, 2, pp. 133–53, Berlin). The Murray fracture finds its continuation in the transverse ranges of southern California. The Clarion fracture is aligned with an active volcanic belt in Mexico. The Clipperton fracture, having passed the axis of the East Pacific rise, runs into the Middle American trench. The varied nature of these oceanic transverse fractures suggests that they essentially predate the Miocene-to-Recent remodelling of the American Pacific coast. The greater age of these fractures is also indicated by their seismic inactivity.

The lateral slip attributed to the East Pacific fractures is mainly concluded from their offsetting of magnetic anomaly belts. The postulated fit of the magnetic pattern, however, amounts to improbably high figures of strike-slip displacement. Therefore, the real nature of these transverse fractures may still be questioned and further interpretations on the origin of the apparent offset structure of the magnetic pattern might be investigated.

[111]) B. C. HEEZEN, M. THARP, and M. EWING (1959); B. C. HEEZEN and M. EWING (1961).

one another and show great similarity to topographic profiles across the East African rift valleys as well. On the Mid-Atlantic Ridge there is a crest zone of extremely rugged relief and a region of broader rugged relief on either side. The whole rise has a span of some 1,500 km in width and its crest province lies generally not more than 1,000 m below sea-level. A median rift valley, some 1,000 to 3,000 m deep and some 25 to 50 km wide runs consistently along the crest axis. The median rift valley belt is presumably not a continuous, canyon-like feature. It is apparently composed of a series of semi-continuous troughs, somewhat similar in plan to the pattern of the African rifts. All major features of the Atlantic rise including subsidiary ridges and troughs along the flanks parallel the axis of the rise. It is through this general pattern that any transverse offset becomes conspicuous. All over the Atlantic the *earthquakes epicenters* are clustered near the deep median cleft that parts the crest province.

The Mid-Atlantic Ridge emerges in *Iceland*, and the so-called 'central graben' of Iceland is the extension of the median rift. All modern volcanism of Iceland is localized in this zone (Plate XLV). The floor of the 'central graben' is cut by many active fissures, running parallel to boundary faults of the 'graben'. This landward extension of the Mid-Atlantic rift clearly displays a prevalence of tensional tectonic features: The **modern fissures**[112]) in the 'central graben' of Iceland gather along zones of 1–4 km in width and 10–30 km in length. The width of single gaping fissures amounts up to 50 meters. The *extension rate* of three postglacial zones (Reykjanes, Thingvellir, Gjástykki) was investigated by F. BERNAUER[113]) who found an average rate of 3.56 m/km/1,000 years (calculated for the last 5,000 years which is the estimated average age of the surficial rocks involved). It should be noted, however, that according to BERNAUER (1943, pp. 36–40) this extension rate exclusively refers to narrow strips of active fissures (each of the three investigated fissure zones including some 10 to 50 individual gaping fissures). It is inadmissible, therefore, to apply this extension rate to the total width of the 'central graben' of Iceland as has been done in recent papers[114]). In addition to gaping fissures, evidence of **Tertiary tensional tectonics**

[112]) Gaping fissures are called *gjá* (Icel.).

[113]) F. BERNAUER (1939, 1943).

[114]) The misleading interpretation of BERNAUER's statement (written in German) appeared first in R.W. VAN BEMMELEN and M. G. RUTTEN's book on the 'Tablemountains of Northern Iceland' (Leiden, 1955), p. 161; since then it has been quoted frequently, see for example: B. C. HEEZEN (1960, Sci. Am. **203**, p. 104); G. O. RAASCH, *Ed.*, 'Geology of the Arctic', vol. I, p. 629 (Toronto, 1961); S. K. RUNCORN, *Ed.*, 'Continental Drift', p. 264 (London, 1962); R. W. VAN BEMMELEN (1965, Tectonophysics **1**, 5, p. 412).

is revealed by the dilatational effects of dolerite dike swarms cutting Tertiary plateau basalts. In eastern Iceland, in the Reydarfjördur area, along a section 40 km in length over 500 dikes with an aggregate thickness of 1.5 km were observed. The expansion of this section due to dilatation is some 4 per cent[115]). These dikes, generally trending north, are unevenly distributed showing well-marked concentrations around volcanic and subvolcanic centers[116]), *e.g.* the Tertiary *Thingmuli* central volcano, or around the *Sellátur* rhyolite plug. In the same area an additional extension, amounting to some 10 per cent of the amount due to dike intrusion, was concluded from displacements on high-angle fractures[117]). This faulting, however, is believed to be later than the dike intrusion, and due to 'entirely different stress conditions'[118]).

On Iceland, that is in the crestal province of the Mid-Atlantic Ridge, there is thus proof of remarkable tensional effects in Tertiary as well as recent times. Yet the quantitative aspects of these features have not been approached in a judicious way. With regard to lateral crustal displacement in oceanic regions there is unfortunately still a tendency to base factual statements on artifacts and guesswork[119]). Any interpretation of tensional structures exposed on Iceland, of course, bears strongly on the type of mechanism that is thought to have brought about the rise of the Mid-Atlantic Ridge. Whatever it might be, the process that forms oceanic rises appears capable of elevating the sea floor at least some 2 km for prolonged periods. Therefore, as early as 1954, H. H. HESS suggested that the rise of the Mid-Atlantic Ridge might result from *mantle convection* tearing the ocean crust apart. By means of such 'sea floor spreading', over the up-welling site of the convection, *i.e.*, the crest of the rise, the crustal material would give place to emerging 'serpentinized mantle rocks' (hypothesis of sub-Mohorovičič serpentinization of peridotite by water rising from the mantle), and basaltic magma would then be enabled to ascend as well. Before oceanic *heat-flow* measurements were made, it was expected that the values from deep ocean basins would be remarkably below continental values. To the surprise of the authorities, heat-flow values obtained in the deep ocean basins were approximately equal to those measured on the continents. But values five to six times higher were observed over mid-oceanic rises.

[115]) G. P. L. WALKER (1959, p. 383).

[116]) *Ibid.* (p. 384).

[117]) G. BODVARSSON and G. P. L. WALKER (1964, p. 289).

[118]) G. P. L. WALKER (1959, p. 389).

[119]) As to the area discussed the reader is referred to R. W. VAN BEMMELEN (1965, p. 412) who presents an average rate of widening across the Scandic region of some 3 cm/year on the basis of the papers by L. R. WAGER and E. I. HAMILTON (1964) and G. BODVARSSON and G. P. L. WALKER (1964).

Thus, when such results were published by E. C. BULLARD *et al.*[120]), R. VON HERZEN[121]) and others this gave great encouragement to convection current theorists. In his paper on sea floor relief and mantle convection MENARD (1965) reviews the hypotheses offered. Yet he himself though advocating mantle convection, objects to significant migration of the flanks of oceanic rises away from their crest. Spreading due to convective flow, for instance, at the rate of about 1 cm/year on each flank, was postulated by H. H. HESS (1962). He argued that on the Mesozoic Mid-Pacific Rise (*Darwin Rise*) volcanic islands had been formed at the crest of the rise, and had been truncated and were then gradually carried away from the crest moving laterally into deeper water on the flanks where they are now identifiable as guyots[122]). In contrast, MENARD, (*op. cit.*, p. 359) by demonstrating the actual relief of the subsided Darwin Rise, suggested that vertical movements alone could account for this marine topography. For the Atlantic Ocean, similarly, MENARD (*op. cit.* pp. 360–61) disproved J. T. WILSON's 'evidence from islands' on the spreading of the ocean floor[123]) (deduced from plotting the oldest ages reported for some islands in the Atlantic and Indian Oceans against the distance of these islands from the nearest point on a mic-oceanic ridge).

H. W. MENARD (1965, pp. 328–29) concluded that in the North Atlantic, at least between N. Lats. 30° and 75°, the Mid-Atlantic Ridge is underlain by an extraordinary accumulation of flood basalts. His conclusion is based on the distribution of the '*second seismic layer*'[124]) which shows an average thickness of some 3 km and which is particularly confined to the course of the North Atlantic rise. The exceptional thickness (up to 5 km) of the second layer is consistent for most of the rise although this layer is not recorded at many nearby ocean basin stations. The identification of the layer is based on seismic velocities, distribution and association with volcanic rocks exposed. Its velocities, admittedly, are appropriate for either sedimentary or volcanic rocks,

[120]) E. C. BULLARD, A. E. MAXWELL, and R. REVELLE (1956). Heat flow through the deep sea floor, pp. 153–81, 7 figs., (*in* H. E. LANDSBERG, *Ed.*, Advances in Geophysics **3**), Acad. Press (New York).

[121]) R. VON HERZEN (1959). Heat-flow values from the South-Eastern Pacific, pp. 882–83, 1 fig., Nature **183**, 4665, (London).

[122]) HESS's rate of motion of convection currents (one centimeter per year) is solely based on the supposition that in the Mid-Pacific, guyots 1,000 km away from the center of the rise were truncated 100 million years before those near the center.

[123]) J. T. WILSON (1963) Evidence from islands on the spreading of ocean floors, pp. 536–38, 4 figs., Nature **197**, 4867, (London).

[124]) The reader is referred to the papers by J. and M. EWING (1959), and M. BÅTH (1962) on the crustal structure in the North Atlantic and in Iceland in particular.

but the distribution is difficult to account for unless this layer is volcanic. The pile of early Tertiary basalt floods exposed in the Scoto-Irish region, the Faeroes, Iceland, and Greenland amounts to thicknesses of 1–4 km, which is about the same as the thickness of the second seismic layer underneath the intervening sea floor[125]). Arguing against 'sea-floor spreading' MENARD (*op. cit.* p. 361) emphasized that the thick second seismic layer under the sea floor between the British Isles and Greenland was evidently produced during the same period of Tertiary volcanism. If so, the layer consists of volcanic rocks of similar age (early Tertiary flood basalts) and, consequently, no migration from the crest to the flanks has occurred on the Mid-Atlantic Ridge since early Tertiary times.

The North Atlantic oceanic region covered by Tertiary basalt floods was estimated by MENARD (*op. cit.* pp. 328–29, fig. 6) to cover some 7.3 million square kilometers. This figure, of course, is considerably increased by adding the West Greenland basalts and some conjectural floods north and south on the Mid-Atlantic Ridge. The estimated volume of all basaltic lavas poured out over the Brito-Arctic province then reaches some 15 million cubic kilometers. This implies that the median rise of the North Atlantic was apparently the site of exceptional endogenic heating in the early Tertiary as was the Darwin Rise in the Mesozoic. That the northern Mid-Atlantic Ridge subsided as did the Darwin Rise, however, cannot be shown on the basis of marine topography and geology because of the paucity of known guyots in the North Atlantic. Yet from the subaerial parts of the Brito-Arctic province there is indeed evidence that the history of the North Atlantic rise approximately paralleled that of the Darwin Rise.

Oceanic rises take various morphological forms that are gradational from very broad rises with gentle slopes to narrow, steep-sides ridges. Many show median rifts and seismic activity, and others are flat-topped and aseismical. Volcanoes, both islands and seamounts, are very common in all oceans. They are distributed over the crestal provinces of seismically active rises, but are at least as numerous on the flanks and elsewhere in ocean basins. The western Central Pacific is an extensive basin where volcanoes are abundant. This region, however, is not the site of an existing active rise but of the collapsed Darwin Rise. Taking into account the varied features of oceanic rises all over the globe, MENARD (1958, p. 1181) eventually postulated that their gradation in morphological forms reflects a developmental sequence. Consequently,

[125]) At this point, however, I have to insert that the Brito-Arctic flood basalts should not be considered as equally regularly distributed. There seems to be a preferred occurrence of eruptive activity in areas where tectonic major zones intersect (see later).

this implies that *oceanic rises cannot be permanent.* It is namely the history of the *Darwin Rise*[126]) that elucidates the transient character of an oceanic rise. It suggests that if rises are generally heated and become the sites of abundant large volcanoes, including submarine flood basalts (such as the archipelagic aprons in the western Central Pacific), that this is already a late stage of development which most existing and seismically active rises have not yet reached.

The rise of the Brito-Arctic eruptive field

In his classic work on Britain's ancient volcanoes Sir ARCHIBALD GEIKIE pointed out that the Scoto-Irish basalt accumulations were remnants of extensive plateaus made up of lavas extruded from fissures[127]). A. GEIKIE (1897) devoted one chapter of his second volume particularly to the historic *fissure eruptions* on Iceland[128]) as "illustrative" of the

[126]) H. W. MENARD (1964, pp. 138–46).

[127]) The *fissure eruption* theory, promulgated by VON RICHTHOFEN and popularized by Sir A. GEIKIE, has been generally accepted for the emplacement of plateau basalts. G. W. TYRRELL (1937) pointed out that no-one approves any longer of the VON RICHTHOFEN's concept of productive fissures hundreds of kilometers in length and of considerable width. On the contrary, it is held that the Tertiary basaltic lava floods originated from comparatively short and narrow fissures distributed over a wide area. Long-continued intermittent extrusion is assumed, either by quiet sheet-flood eruption from all parts of the fissure or by more violent eruptions from numerous separated vents along the fissure. Both types of eruption have been observed in modern Hawaiian lava streams. In Iceland, however, the classic Laki fissure type is of the cone-chain mode.

[128]) The largest lava stream ever recorded in historic time, the Laki lava flow in southern Iceland, was emitted 200 years ago from the '*Lakagígar*'—a row of craters stretching over some 25 km. The eruption lasted seven months. The lavas, spread over a total area of 565 sq. km, were estimated to be 12 to 15 cubic kilometers in volume. Severe earthquakes preceded this eruption. The actual outbreak began June 8, 1783, with tremendous explosions. Ash ejected from the Laki fissure rained over a wide region as far as Scotland and Norway where ash occurred in sufficient quantity to damage crops. On June 11, effusion of lava eventually began; streams poured out from twenty-two vents and produced basalt floods. Although these lavas and floods of glacier waters caused great damage, still more disastrous was the bluish sulphur haze that lay all summer over Iceland and caused famine and disease. This national disaster, still referred to as the "Haze Famine", resulted in the loss of 9,200 human lives and 50 to 80 per cent of the domestic livestock.

The laki lavas partly covered older basalt flows which originated from a 30 km long system of fissures collectively called '*Eldgjá*' situated immediately southeast of the Laki fissure and of similar strike, *i.e.* northeast-southwest. The Eldgjá flows were estimated by T. THORODDSEN (1905, p. 138) to be 9 cubic kilometers in volume and still considered to be of historic age. Yet, more recently it was found that at least the two main flows were of prehistoric age based on both tephrochronology and radiocarbon dating (S. THORARINSSON, 1960 a, p. 41).

Tertiary volcanic history. Although this comparison is not necessarily correct it holds good for many of the characteristics of the building up of '*plateau basalts*' as he called them. Taking up GEIKIE's description of lava streams that flooded extensive areas and buried the heights and hollows of old land, G. W. TYRRELL (1937) coined the term **flood basalts.**

It is true that all over the Brito-Arctic province fossil plants and even coal-seams were found early in sub and intra-basaltic sediments and attracted both scientific[129]) and economic[130]) attention. Also the mode of formation of intra-basaltic sediments, particularly of red beds, has been discussed[131]). Yet the conclusive point was only reached by TYRRELL (*op. cit.* p. 100) when he emphasized that these basalt floods were poured out on continental surfaces and were usually of subaerial origin. Although basalt plateaus build up much faster than any other rock complexes do—in the Brito-Arctic province some 15 million cubic kilometers of volcanic rocks were emplaced—the accumulation of these giant lava piles does take considerable time. The lava floods were not poured out one upon another continuously, but instead enough time elapsed for *subaerial decay* of the surface of the lava to occur. During these intermissions sediments of aeolian or lacustrine type, including wind-blown ash or tuff, old soils, even bauxitic and lateritic deposits as well as coal may have been formed, and covered by later lava flows which were thus spread over a perfectly levelled land. It is for this reason that the flood basalts appear to be extremely regular and well bedded over great distances. TYRRELL also noted that in general these floods are remarkably free of conspicuous cones or any surficial signs of central volcanoes.

The very fact that all over the Brito-Arctic province the expanses of basalt flowed over dry land and were the subject of continued subaerial erosion demonstrates a particularly uniform epeirogenic history throughout the province. This can be easily shown by summarizing the early Cenozoic features to be seen in West and East Greenland, in Great Britain, and on the islands in the Atlantic Ocean.

1) West Greenland

Stratigraphy and environment of sedimentation. — In Central West Greenland, Mesozoic and Cenozoic formations occupy parts of Disko

[129]) OSWALD HEER (1809–1883) a pioneer in paleobotany, distinguished for his research on Tertiary plants and insects, published seven volumes on the floras associated with the Brito-Arctic basalt province under the title "Flora fossilis Arctica" (vol. I, 1868, vol. VII, 1883).

[130]) Coal is mined on the Faeroes (Tertiary) and in West Greenland (Cretaceous). Bauxite and iron ore have been mined in Ireland (Tertiary).

[131]) L. HAWKES (1916).

island, Nûgssuaq and Svartenhuk peninsulas, and some smaller areas on the adjacent islands. The sedimentary rocks, almost exclusively clastics and mostly of continental or epicontinental facies, lie on an uneven surface on top of deeply weathered Precambrian basement rocks. The marine interbeds, mainly in the form of black bituminous shales, indicate temporary inundations in the *Upper Cretaceous* (Coniacian (Emscher), Senonian, Danian) as well as in the *Lower Tertiary* (Paleocene and (?) Eocene). At the base of both the Danian and the Paleocene there are coarse clastics (deltaic deposits) resting with slight angular unconformity on older strata. There is thus evidence of *epeirogenic displacements* including *block faulting* about northerly striking fractures. At Nûgssuaq peninsula, for instance, at a time after the deposition of marine Lower Tertiary sediments, a prominent fault threw down the western block for some 2,000 m. The region, however, was remarkably levelled when the major outpourings of flood basalts set in.

The total thickness of the sedimentary accumulations amounts to some 2,000 m[132]). E. B. Koch (1964, p. 537) described the whole succession in terms of coastal deposits adjacent to a 'potential source area of erosional debris'. He called attention to the inland ice region east of Disko Bugt where a conspicuously irregular relief of the ice-rock interface was computed by J. J. Holtzscherer (1954, fig. 18). Its overall feature is an extensive depression rimmed by almost continuous highlands in which a gap faces distinctively towards Disko Bugt. Much of this depression lies below sea-level involving two narrow troughs, more than –250 m deep and of east-northeasterly strike. Both systems apparently have a common outlet into Disko Bugt. E. B. Koch visualized the above mentioned source of early Cenozoic clastics in the highlands that still surround and subdivide the depressed region. Koch's opinion that the present subglacial topography traces back to a pre-Quaternary drainage system 'is supported by the presence of a "fossil" channel several hundred meters deep, eroded into older deposits in the area of sedimentation during the regression between Danian and Paleocene, which winds its way along the south coast of the Nûgssuaq peninsula. During the early Paleocene this channel was filled with fluviatile sediments [Upper Atanikerdluk Formation], and may have formed a part of the same drainage system as the supposed Disko Bugt outlet' (*op. cit.* p. 537).

In the terrestrial formations of both the Cretaceous and Tertiary there are rich *fossil floras.* Coal-bearing formations, however, such as the **economic coal seams** in the "Atane Formation" on Disko island[133])

[132]) S. Munck and A. Noe-Nygaard (1957, p. 248).

[133]) At Qutdligssat, some 30,000 tons of coal are mined per year from the Upper Cretaceous "*Atane Formation*", a succession of alternating sandstones and shales.

are exclusively Cretaceous[134]) in age. The well known **Arcto-Tertiary flora**[135]) is of *Lower Paleocene* age. It mainly occurs in delta deposits, which could accurately be determined on the basis of a rich marine fauna (A. ROSENKRANTZ, 1951).

Surface volcanism. — Cenozoic volcanism in West Greenland commenced in the Danian (uppermost Cretaceous). Andesitic ash layers were found to be interstratified with marine fossiliferous beds. Subsequent layers of andesito-basaltic and eventually of basaltic ash were found in still younger Danian and Paleocene strata respectively. The first volcanic outbursts thus were explosive and also indicate 'a certain degree of contamination' (S. MUNCK and A. NOE-NYGAARD, 1957, p. 250). The outpourings of actual basalt flows began in the Paleocene only. The lowermost lava sheets ("Basalt breccia division") are considered to be *submarine flows*, as suggested by both their pillow structures and by the material of the pillow-lava "breccia" itself which is to a high degree glassy. The submarine flows alternate with shaly and sandy sediments and glassy tuff layers as well. The "breccia division" varies in thickness from place to place (*e.g.* 100 to 150 m at Nûgssuaq peninsula) and rests almost everywhere on marine strata. The pillow lavas and pillow-lava breccias evidently filled up irregular depressions on a shallow sea floor. When the accumulations reached sea-level—over the West Greenland eruptive field this happened apparently at different times—the volcanic activity was continued with *subaerial basalt floods* ("plateau basalt division"). The latter show slaggy surfaces and beautiful flow phenomena on the surface of the individual sheets (A. NOE-NYGAARD, 1942, p. 71). The subaerial flows are interlayered with sedimentary beds, among which tuffs play an important rôle. Fossil plants from intrabasaltic beds suggest a pre-Miocene age (presumably Eocene[136])).

As to the *level of extrusion*, A. NOE-NYGAARD concluded that during

[134]) Another sequence of clastic sediments with minor coal-bearing zones is the "*Kome Formation*". Its Cretaceous age has never been doubted, yet the accuracy of O. HEER's determination of 'Lower Cretaceous' became a matter of discussion when more recent evidence favored a Late Cretaceous age also for this formation (see E. B. KOCH, 1964, pp. 538–39).

[135]) The *Arcto-Tertiary flora* is essentially West Greenland's classic Tertiary flora of Atanikerdluk (identified as of 'Miocene' age by O. HEER, 1869, 1882, 1883). Its *Paleocene* age has only been established in recent years. According to E. B. KOCH (1963, 1964) a few conifers have been recorded in this flora, but angiosperms, including several modern genera, are dominant. Its early Tertiary character is due to the survival of some typical Cretaceous genera and to the occurrence of some old groups now monotypic or poor in genera and species.

[136]) E. B. KOCH (1964, pp. 546–47).

the great production of lava streams the whole region had most likely been steadily sinking, so that the level of outpourings 'most of the time has kept almost constantly a little above sea-level' (*l.c.*). This is also indicated by recurrences of the "breccia facies" occurring locally within the pile of subaerial flood basalts. In general, the "plateau basalt division" rests on the submarine "breccia division". At various places, however, the subaerial flows spread further across adjacent land surfaces. Examples are also quoted of submarine flows encroaching on a Tertiary coast and then having the characteristics of subaerial flows on the land.

In the northern part of West Greenland's basalt region (Svartenhuk peninsula[137]), Ubekendt Ejland[138]) the original thickness of the basalt pile might have been as much as 10 km. The base of the lava pile visible on Svartenhuk peninsula is not exposed farther to the south on Ubekendt Ejland, nor does the basal "breccia division" occur on this island. The top of the lava pile on Ubekendt Ejland might, therefore, be regarded as the youngest lavas in West Greenland. On both Svartenhuk and Ubekendt Ejland, the whole succession of flood basalts is tilted and down-flexured towards the southwest[139]). There is no unconformity within the basalt succession so that the subsidence and tilting is considered to have taken place after all the major events of volcanicity. This is in contrast to Nûgssuaq peninsula, situated farther south, where an angular unconformity within the plateau itself indicates a westerly tilting that occurred at some time during the volcanic activity[140]).

Intrusions, closely related to the surface volcanism occurred at various times. *Dolerite* intrusions, for example were found to have settled along the major fault zone cutting north-northwesterly across Nûgssuaq peninsula. Minor dikes of grano-dioritic and alkali-granitic *aplites* were apparently associated with them[141]). A younger group of sills and dikes represents an *ultrabasic suite* showing a trend of differentiation from peridotitic to gabbroic to syenitic rocks[142]). On Ubekendt Ejland, the southwesterly dipping pile of basalt lavas is cut by large numbers of basic dikes and sills (picritic and tholeiitic types)[143]). At the southern tip of the island, however, a *composite plutonic stock* was emplaced; this

[137]) A. Noe-Nygaard (1942, pp. 68, 71–72).

[138]) H. I. Drever and P. M. Game (1948, p. 10).

[139]) On Svartenhuk peninsula the plateau formation dips southwesterly at an average angle of 15–20°; on Ubekendt Ejland the average dip is 20–25°.

[140]) A. Noe-Nygaard (1942, p. 72).

[141]) S. Munck (1945).

[142]) A. Noe-Nygaard (1946, pp. 56–57).

[143]) H. I. Drever (1956).

includes granophyre, quartz-syenite and banded gabbro[144]). At the western tip of the island, surrounded by the topmost lavas of the plateau, remnants of a *volcanic neck*[145]) are exposed. The upper group of lava streams, therefore is thought to represent products of *central eruptions* from that volcano called Erqa[146]).

2) East Greenland

When discussing Upper Cretaceous to Lower Tertiary sedimentation in West Greenland it was mentioned (p. 185) that beneath the inland ice-sheet east of Disko Bugt there exists a remarkable depression of varied and irregular relief. This area was investigated and contoured by P.-E. VICTOR and his co-workers[147]) in the early fifties. However, it had been previously discussed by L. KOCH (1923, 1950) on the basis of hypsometrical studies of Greenland's topography. KOCH concluded that '*there is a distinct depression right across Greenland*[148]), a depression which shows itself not only in the altitudinal conditions of the inland ice but also appears plainly in the topography of both the east and west coast' (1923, p. 47). As to the origin of this feature he advanced the theory that parts of Greenland were subjected to *uplift* 'with the result that the country had broken right across, and thus been divided into a northern and a southern block, both tilted towards the north' (1950, p. 7). He found suggestion that 'the *basalts* seem to be connected with the depression' (1923, p. 62) and that the depressional zone 'is situated exactly in the *continuation of the great submarine basalt ridge* [across the Atlantic]' (*op. cit.*, p. 59). This connection relates both to location and to time. Although KOCH was aware that he only could 'point out some questions whose solution is reserved for the future' he involved in his hypsographic studies the position of the sub-basaltic surface as well. From this it became evident that 'the basalts on both coasts prove to be situated at the exact spot where the low gneiss country is suddenly replaced by 2,000-meter high mountains. It would seem that there is a connection between the depression and the basalt areas' (*l.c.*). KOCH evaluated also whether the split of Greenland into a northern and a southern block might date farther back than Tertiary times. However, he reached the conclusion: 'The theory that the depression is simply a

[144]) H. I. DREVER (1958, pp. 198, 206–08).

[145]) H. I. DREVER and P. M. GAME (1948, pp. 12–13, 20–24).

[146]) H. I. DREVER (1958, pp. 200–01).

[147]) "Expéditions Polaires Françaises, 1948–51".

[148]) KOCH suggested a depressional zone running from Disko Bugt (west coast, 69° N) to Kangerdlugssuaq (east coast, 68° N).

direct continuation of the *great Tertiary fissure* is ... the most natural explanation. We know that there have been great movements ... in mid-Greenland since the Tertiary period, marine fossiliferous strata having risen several hundred meters since then. If the depression is a Tertiary fissure, the consequence would be that the gneiss planes [*sub-basaltic land surface*] would be *displaced vertically* along the fissure about 2,000 meters in relation to each other' (*op. cit.*, p. 63).

It is remarkable that LAUGE KOCH started thinking about the relationship of physiography and Tertiary geology at a time when East Greenland's stratigraphy and tectonics were scarcely known and years before his field research was transferred to this part of Greenland. Yet thirty years of subsequent geological investigations did not work out the entire sequence of geologic formations. A comprehensive investigation of East Greenland's Tertiary eruptive field was planned, but for various reasons never completed. It is true that in the scope of KOCH's expeditions a number of petrologic studies were made on Tertiary igneous rocks, particularly on plutonic types. Lava flows and minor intrusives were studied as well. At the same time paleontologists and stratigraphers concerned with Mesozoic strata added excellent observations of intrusive and extrusive phenomena. A. VISCHER (1943), in particular, included the Tertiary volcanicity in his structural study of the coastal area between 74° and 75° N. Thus, north of the great basalt plateau of Scoresby Sund, on KOCH's early expeditions efforts were already made to analyze the geological setting of the Tertiary igneous suite. Such attempts[149]), however, were not entirely successful at that stage of geologic exploration, as products of Devonian volcanism were encountered and considered as Tertiary eruptives. In view of this, therefore, on his post-War expeditions LAUGE KOCH was right to postpone a through study of the entire Tertiary eruptive field until all pre-basaltic formations were accurately known. With regard to prospecting work on economic deposits of galena and molybdenite priority was also given to the investigation of the intrusive centers situated around Kong Oscars Fjord (see Map 3).

On the other hand, south of Scoresby Sund, L. R. WAGER[150]) and his co-workers had initiated in those thirty years a successful investiga-

[149]) H. G. BACKLUND and D. MALMQVIST (1932, 1935).

[150]) The late Prof. L. R. WAGER (Oxford University) started work as a member of WATKINS's "British Arctic Air-Route Expedition 1930–31". In 1932, he joined a Danish expedition led by EJNAR MIKKELSEN, and finally, in 1935, he started his own series of "British East Greenland Expeditions". These were aimed mainly at a detailed study of the Tertiary plutonic centers, the best known of which is the Skærgaard intrusion (L. R. WAGER and W. A. DEER, 1939).

tion of the basalt plateau and in particular the associated plutonic center around Kangerdlugssuaq. In conclusion, it may be said that in East Greenland some of the events of Tertiary igneous activity are well recorded, but the entire episode is still insufficiently studied.

Early Tertiary uplift. — From the papers by L. KOCH (1929 b, p. 292; 1950, pp. 5–8), A. VISCHER (1943, pp. 162–64), L. R. WAGER (1947, pp. 57–59) and others it becomes evident that the middle stretch of East Greenland, *i.e.* from about 65° to 75° N, reveals indeed an impressive early Tertiary uplift. In the stratigraphic column the effects of this event are shown by the change from the widespread Upper Cretaceous inundation[151]) to the equally widespread Tertiary regression. From two areas, namely Wollaston Forland (75° N) and Scoresby Sund (70°–71° N) some detailed information is at hand. In both areas, prior to the onset of surface volcanism the elevated land was subjected to intense erosional processes which resulted in the formation of a slightly hilly ground with distinct valley sites (Fig. 75). The early Tertiary land was drained essentially towards the east, that is by a fairly similar pattern to that of the present day. In the Scoresby Sund area[152]), in particular, the subbasaltic land surface slopes towards the southeast (Fig. 76), and the subsequent flooding by basaltic lavas had its source in the east. The oldest flows filled up the valleys, the younger ones drowned the hills encroaching successively westward across the dipping land surface (tilted peneplain?). The same relationship, a slightly sloping ground flooded by lava streams from the east, was observed in Wollaston Forland[153]).

Commencement of surface volcanism. — It was mentioned on p. 164 that in the Kangerdlugssuaq region (68° N) *marine Senonian deposits* were laid upon a fairly even surface truncating the Precambrian basement complex. This shallow water formation was followed—apparently with no great interval of time—by sandstones and conglomerates bearing fossil plants and coal[154]). The whole succession, including the marine basal sequence, is considered to form one stratigraphic unit, called the "Kangerdlugssuaq Sedimentary Series"[155]). Associated with coal-bearing

[151]) Remnants of *Upper Cretaceous* marine deposits are known from Hold with Hope (74° N), Traill Ø (72°30′ N), and Kangerdlugssuaq (68° N), cf. p. 164.

[152]) E. WENK (1961 b, pp. 46–47).

[153]) A. VISCHER (1943, pp. 91–94).

[154]) A. C. SEWARD and W. N. EDWARDS (1941, p. 175) consider these plants as of 'very early Eocene' age; they admit, however, that whether some of these may be uppermost Cretaceous rather than lowest 'Eocene' cannot yet be decided.

[155]) L. R. WAGER (1947, pp. 12–19).

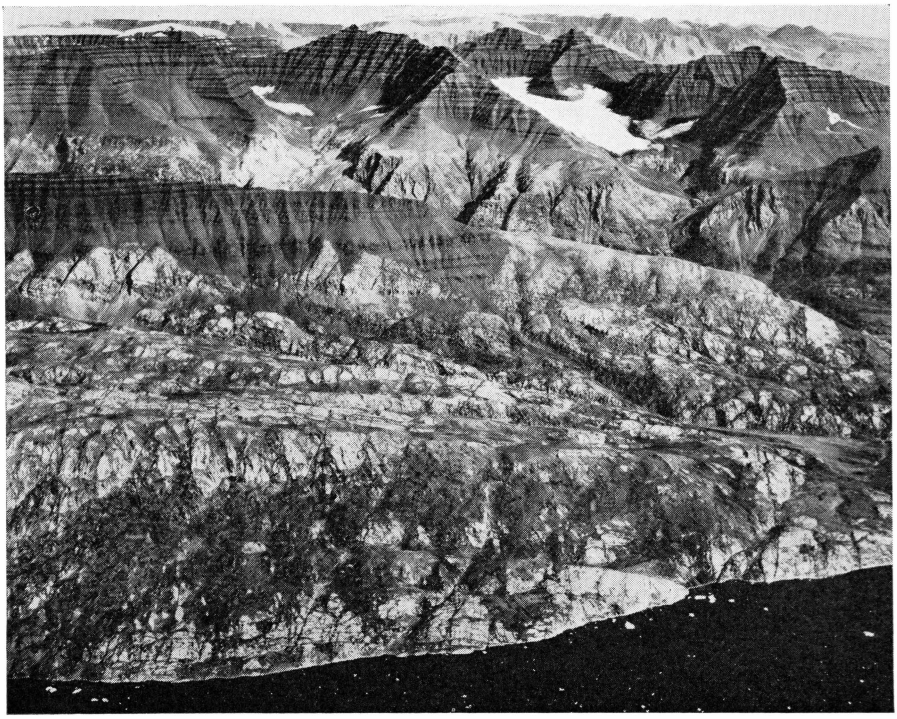


Fig. 75. At the north coast of Gaasefjord, the base of the Tertiary basalt plateau is exposed over a distance of one hundred kilometers. The photograph taken some 20 km southwest of Gaase Pynt (*i.e.* the eastern tip of Gaaseland) displays notable valleys furrowing the levelled early Tertiary land surface. The lava floods filled the valley sites and eventually covered the whole country. — Air-phot. M. BRENNEISEN, 1949.

deposits is a conglomerate containing rolled *basalt pebbles* indicating that surface volcanism had already started at that time. This is consistent with WAGER's conclusion that some early lava flows in the Kangerdlugssuaq region were extruded under water[156]), and that also pyroclastic beds accumulated in the same environment. There is thus evidence that in East Greenland as in West Greenland the Cenozoic igneous activity commenced in uppermost Cretaceous times.

Major volcanicity, its areal distribution and structural setting. — Substantial extrusive activity lasted through Paleocene and Eocene

[156]) Evidence of submarine extrusion was found in Mikis and J. C. Jacobsens Fjords, both situated immediately east of the mouth of Kangerdlugssuaq, cf. L. R. WAGER (1934, p. 26; 1947, pp. 20, 23–24, 28), L. R. WAGER and W. A. DEER (1939, pp. 17–18).

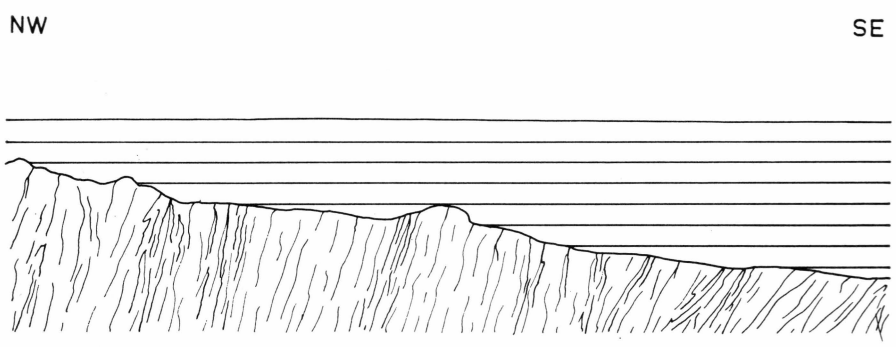


Fig. 76. Diagrammatic section showing the sloping base of the Eocene basalt plateau in the Scoresby Sund region. — Adapted from E. WENK (1961 b, p. 46).

times and may not have ceased until the Oligocene (or even the Miocene?). The areal distribution of East Greenland's Tertiary igneous field is shown on Fig. 77. It will be noted that both extrusive and intrusive features are essentially confined to the region south of the 76th parallel. Thus the Tertiary igneous rocks cover much the same area that was formerly the site of the Central East Greenland geosyncline from late Precambrian through Lower Paleozoic times. Future research may decide whether this is arbitraty or in fact related to the variation in tectonic style of the Caledonian mountain belt. Fig. 77 shows moreover that East Greenland's Tertiary igneous rocks are grouped into four distinctive regional fields, each showing different tectono-magmatic features (see later). Three of them were built up essentially by surface volcanism (lava floods):

(i) The *southern basalt plateau* between Scoresby Sund (70° N) and Kangerdlugssuaq (68° N), covering roughly one million square kilometers where the sheeted basalts attain thicknesses of 4,000 to over 6,000 meters. The area referred to as the "southern basalt area"[157]) (cf. Pl. I) has also been called "Geikies Plateau"[158]). (The name *Knud Rasmussens Land*, for a long time applied to this area, was recently transferred to North Greenland by the Danish committee[159])).

(ii) The *northern coastal plateau region* extending from Kejser Franz Josephs Fjord (73° N) to Shannon Ø (75°30′ N).

[157]) O. NORDENSKJÖLD (1907, p. 216); L. KOCH (1929 a, p. 197).
[158]) L. KOCH (1935 b, p. 116; L. R. WAGER (1947, pl. 6).
[159]) Stednavneudvalget for Grønland.

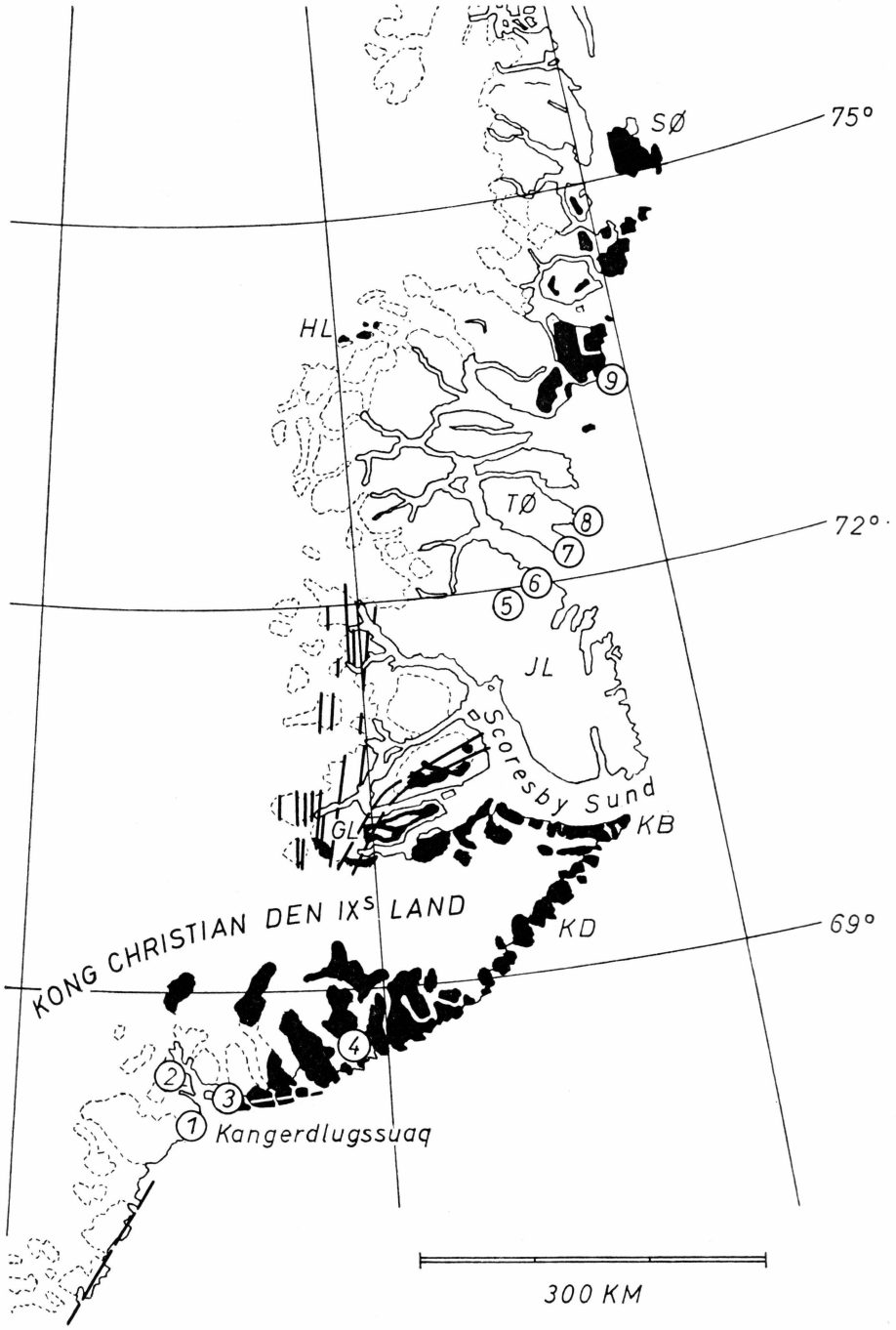


Fig. 77. Outline map of East Greenland's Tertiary eruptive field. Flood basalts are shown in solid black, regional dike swarms by heavy lines. Nos. 1 to 9 indicate the intrusive centers listed on pp. 236—37. *KB* = Kap Brewster, *KD* = Kap Dalton, *GL* = Gaaseland, *HL* = Hobbs Land, *SØ* = Shannon Ø, *TØ* = Traill Ø.

(iii) The *Hobbs Land plateau* emerging at the edge of the inland ice at 74° N (cf. Fig. 7).

The fourth field, occupying the *central coastal region* (iv) between Kejser Franz Josephs Fjord and Scoresby Sund, includes a great number of minor dolerite intrusions as well as a row of plutonic centers around Kong Oscars Fjord.

According to L. R. WAGER (1947, p. 28) the lavas now exposed in the huge southern plateau, except those around the mouth of Kangerdlugssuaq, were extruded subaerially. Yet sinking of the lava pile concomitantly with extrusion must have taken place over the whole region. This is particularly indicated by the presence of *marine Eocene beds* at Kap Dalton (69°25′ N). This succession rests transgressively on top of the lava pile. Both the sediments and their basaltic pavement were later on subjected to faulting and tilting and the type locality of the "*Kap Dalton Series*" is a small arbitrary remnant preserved on a down-faulted block (L. R. WAGER, 1935). Marine beds referred to the "Kap Dalton Series" were also found at Kap Brewster (70°10′ N) where they rest with a basal conglomerate on pillow lavas and brecciated volcanics (M. Y. HASSAN, 1953, pp. 8–13). Inundation thus commenced while some volcanic activity still proceeded. At Kap Brewster, another post-basalt succession, the "*Kap Brewster Series*", indicates a renewed transgression of the sea in Miocene times (*l. c.*). We may thus conclude that the building up of the southern basalt plateau, which commenced at the very end of Cretaceous times, was apparently completed by middle to late Eocene age, *i. e.*, the transgression of the Kap Dalton beds. This dating, when applied to the standard time scale, leaves an interval of time of at least some 10–20 million years for the emplacement of the 6 km thick pile of sheeted basalts. The age relationship found in the southern basalt plateau is presumably valid for the northern basalt fields as well.

The crustal flexure south of Scoresby Sund. — Information on the tectonic history following the major event of surface volcanism, again is mainly derived from the southern basalt plateau and is from the papers by L. R. WAGER and W. A. DEER (1938) and L. R. WAGER (1940, 1947). It ought to be mentioned, however, that the coastal structure developed in the Kangerdlugssuaq region—a giant down-warp of the entire basalt plateau about a northeasterly trending flexure—is of particular significance to the southern section of East Greenland's eruptive field only. It has no direct bearing on the structures exposed on the mainland

farther north. Yet this flexure is vital to the whole crustal structure off Greenland's east coast thus providing a link to the structural setting of Iceland.

It was stated earlier that the building up of the great southern basalt plateau was accompanied by a gentle subsidence of the whole region. For various reasons the level of lava extrusion was presumably never very high above sea-level. In this respect the development of the East Greenland plateau was fairly similar to that of West Greenland (cf. p. 186). WAGER (1947, p. 52) saw in this 'passive' subsidence of the growing basalt pile an isostatic adjustment 'so that there is a maintenance of approximate hydrostatic equilibrium in the crust'. When the major surface vocanism ceased the plateau partly sank below sea-level. At that time, the Eocene "Kap Dalton Series" transgressed across the horizontal plane lava pile. This series received its supply first from the adjacent igneous field, but later on clastics were poured into the shallow sea from metamorphic and sedimentary complexes, presumably from the north[160]). The highground in the north, including what appears to be today the Staunings Alper massif and its sedimentary foreland, took part in a widespread epeirogenic uplift that affected the present coastal mountains southwards as far as Kangerdlugssuaq. This powerful uplift succeeding the formation of the southern basalt plateau gave rise to what is now the highest part of East Greenland's coastal belt. A simultaneous down-sinking of the area to the south-east, the basalt pile being submerged by the sea, produced Danmarks Strædet. Between these regions of opposite vertical movement the plateau was bent into the conspicuous flexure. Where the down-warping was intense with dips of more than 10°, a *swarm of dolerite dikes* settled into the convex part of the crustal monocline[161]). The intensive flexuring and its associated dike swarm occur along much of the coast between 66° and 70° N. According to L. R. WAGER and W. A. DEER (1938) it is likely that all the flexuring took place during the same limited period of time. It is also held 'almost certainly' that the coastal flexure came into being after the formation of the "Kap Dalton Series". In his summary paper of 1947, L. R. WAGER confirmed this view, yet at that time, the occurrence of the presumably Miocene "Kap Brewster Series"

[160]) Cf. L. R. WAGER (1935, pp. 10, 26–30).

[161]) L. R. WAGER and W. A. DEER (1938, p. 40) observed a constant relationship between the following three factors: the dip of the lavas, the density of the swarm, and the dip of the dikes. The lavas where preserved away from the coast, have low dips not exceeding 3°, but as the present coast line is approached the dip increases. The dike swarm begins where the dip reaches about 10°, while the densest part of the swarm is associated with dips of 30–60°.

was not known. A more accurate dating of the flexure formation has thus to be approached by means of isotopic dating of the related dike rocks.

The epeirogenic movement revealed by the Kangerdlugssuaq coastal structure can be seen to have produced relative vertical displacement of land and sea areas amounting to some 8 kilometers[162]). Yet, L. R. WAGER (1947, p. 47) did not wish to attribute all of this impressive differential movement to the coastal flexure stage. He suggested that the total movement as now concluded from the mutual relation of reference planes is a compound of: (1) differential sinking of the growing lava pile, (2) epeirogenic major movement and associated flexuring, and (3) possible later up-warping of the highground as a result of isostatic adjustment to erosion and glaciation[163]). The displacement related to flexuring was presumably greatest in the Kangerdlugssuaq region. The crustal warp apparently continues for some hundred or so kilometers to north and south, though it is likely that its amplitude may decrease. It is remarkable how closely the flexure line and its associated dike swarm coincides with the general trend of the present coast. At the mouth of Kangerdlugssuaq, accordingly, the flexure changes in direction through 50°, that is from north-northeast to east-northeast. Farther north, along Blosseville Kyst, the curvature reverses[164]). The Tertiary coastal structure south of Scoresby Sund—a largely *fractureless monocline of curving trend*—shows thus characteristics quite different from the linear block fault tectonics that developed north of Scoresby Sund through Mesozoic times and was still active in the Tertiary. H. CLOOS (1940, p. 181) has briefly touched upon the question whether the Kangerdlugssuaq coastal flexure may not overlie step faulting comparable with the visible block-fault tectonics of the northern area. For this there is no evidence, says L. R. WAGER (1947, p. 51) and concludes that similar stresses evidently have produced different types of tectonic response in the two areas. He considers the deep burial of the sial layer by the immense lava pile and the general heating due to igneous activity as important factors of the development of the flexure, which thus reflects a sort of foundering of the subsided crust. A possible mechanism involving subcrustal removal of material has been suggested in the paper by L. R. WAGER and W. A. DEER (1938) and further discussed by L. R. WAGER (1947). The hypothesis of subcrustal migration of material (in the sense of thinning and thickening of layers) seems to

[162]) See structure section published by L. R. WAGER (1947, p. 37).

[163]) L. R. WAGER (1933, p. 155) concluded that the Greenland ice cap 'which seems to have originated contemporaneously with the main uplift, is believed to have been in existence since Miocene times'.

[164]) Compare figs. 5 and 6 published by L. R. WAGER (1947, p. 33).

WAGER to be the most promising line of explanation. This migration took place in a basaltic layer intermediate in position between the sial and the Upper Mantle (see WAGER, 1947, p. 54).

The emplacement of plutonic centers. — East Greenland's plutonic centers and sub-volcanoes involve a great variety of rocks, mainly of alkaline types. This is in striking contrast to the monotonous lava floods and dike intrusions of basaltic composition. On the map (cf. Fig. 77) the plutonic centers are scattered along a northeasterly running line some 700 km in length. The southernmost complex occurs at Kap Gustav Holm (66°30′ N), the northernmost at Kap Broer Ruys (73°30′ N). It is interesting to note that this conspicuous alignment of plutons is situated approximately perpendicular to the trend of the Brito-Icelandic-Greenlandic major belt. Although some of these bodies have to be considered as sub-volcanoes and hence shallow intrusions, they require at least some cover at the time of their emplacement. Thus the mere fact that they are unroofed now reveals a considerable denudation since the time of their emplacement. At the various intrusions, however, the cover had been stripped off unevenly. As an example I refer to the row of plutons between 72° N and 73°30′ N, shown on Map 3. There is evidence that from north to south the truncation cuts progressively deeper into the plutonic structures. The Kap Broer Ruys complex, though exposed approximately at sea-level, still carries a fairly complete roof. In contrast, the plutons around Kong Oscars Fjord, including the up to 2,000 m high Werner Bjerge massif, are for the most part unroofed. It is true that the plutonic centers concerned occur in different tectonic blocks of the Mesozoic fault system. Moreover, their magma-tectonic depth may be individual, referable to local conditions. Yet part of this striking difference in truncation level has to be explained in terms of post-intrusive vertical displacement. The position of the Werner Bjerge massif, in particular, coincides with the morphological superelevation of the serrated Staunings Alper, which gradually replace the flat-topped mountains of the inner branches of the Scoresby Sund and the Kejser Franz Josephs Fjord systems. The doming of this area apparently followed the emplacement of the Tertiary plutons but certainly preceded the time of glaciation[165]). However, due to the removal of any Tertiary sedimentary beds, no accurate stratigraphic dating of the plutonic emplacement can be obtained; it is likely that the plutons around Kong Oscars Fjord postdate the main phase of dolerite dike intrusions.

In the region south of Scoresby Sund, WAGER (1947, p. 46) found that some *basic* intrusions, *e.g.* the Kap Edvard Holm intrusion, were formed during or soon after the main period of basalt outpouring. The

[165]) See footnote p. 196.

suite of *acid* plutonic rocks, mainly of syenitic and alkali-granitic composition, were apparently intruded after the formation of the major flexure and its associated coastal dike swarm. The emplacement of the acid plutonic complexes[166]) mark the close of the Tertiary igneous activity except for a few sporadic dolerite dike swarms.

3) The British Isles

Over the Scoto-Irish field, apart from raised beaches of Quaternary age, Cretaceous formations are the last significant marine deposits. Upper Cretaceous beds transgressed across a pavement that reflected gentle mid-Mesozoic warping accompanied by uplift and erosion. Basal Cenomanian greensands are succeeded, apparently with non-sequence, by the Senonian Chalk. According to T. N. GEORGE (1965) shallow shelf-seas and intermittent subsidence are to be inferred, and a nearby landmass as a source of the sands. There is further evidence that beneath the North Sea over wide areas the Cretaceous accumulated in thicker and more normal sequences (including the Lower Cretaceous). It is unknown whether the Cretaceous beds were originally banked against the Scottish and Welsh highland massifs or extended at times as a thin blanket across all of the British Isles. In any case, at the close of Cretaceous times, over wide areas the chalky beds were upheaved to form land again and were thus removed by erosion in varying degrees. Yet, the sea soon encroached over the south-eastern parts of England where estuarine beds accumulated. There, through Eocene and Oligocene times a coupled basin structure, including the London and Hampshire[167]) basins came into existence.

In contrast to England, in the Scoto-Irish region, block faulting, and warping of considerable extent is recorded for post-Senonian but pre-basaltic times. Thick successions of rocks were removed from horst and dome structures by prolonged erosion, resulting in a completely peneplaned surface by early Tertiary times.

When volcanic eruption started in Britain[168]), basaltic lavas were

[166]) Biotite from alkaline pegmatite (*Kangerdlugssuaq alkaline intrusion*) yielded a Rb/Sr age of 49 ± 2 m.y. (E. I. HAMILTON, 1966, p. 34). According to the standard time scale this figure indicates a *Eocene age* for the intrusion and cooling of the Kangerdlugssuaq alkaline intrusion.

[167]) Although in their present form the *London* and *Hampshire basins* are synclinal structures brought about by Alpine folding, the synclinal hollows were already present in embryo when the Eocene sea invaded the old chalk surface. An east-west running warp of land, separating the two depressional zones, was eventually accentuated in Miocene times to form the present *Wealden dome* structure (cf. D. L. STAMP, 1946, pp. 140–46, 189).

[168]) The reader is referred in particular to the compilatory papers by G. W. TYRRELL (1949), J. E. RICHEY (1961), and F. H. STEWART (1965).

spread over a dry, sub-horizontal land-surface. Considering the post-Cretaceous movements and the subsequent truncation mentioned above, the transgressive overstep[169]) of the basal flood basalts is thus not to be regarded as defining a stripped Cretaceous foundation. As volcanicity proceeded a highly varied landscape was created in the northwestern part of the British Isles. Lava piles up to 2,000 m were built up by repeated outpourings from a number of centers. These are distributed along a broad belt of country from *Skye*, through *Rhum*, *Ardnamurchan*, *Mull*, and *Arran* to the northeastern part of Ireland, namely *Antrim*, *Slieve Gullion* and the *Mourne Mts.* This tract coincides with a postulated sunken trough filled with Triassic, Jurassic and Upper Cretaceous sediments. G. W. Tyrrell (1949, p. 416) interpreted this NNW–SSE running belt as a 'zone of crustal weakness which may continue up to the Faeroes'. Emplacement and spreading of the Scoto-Irish igneous field was apparently controlled by the structural setting of this belt. Ignoring local variations there seems to be the following sequence of igneous events throughout the field: (1) surface volcanism producing *flood basalts* of regional extent, (2) emplacement of local intrusive centers in the form of *central volcanoes* and *ring complexes*, and (3) renewed regional activity leading to the intrusion of extensive north-northwesterly running *dike swarms*, mainly of basaltic composition.

The flood basalts. — Despite the thickness of the basaltic lava piles, the flows are seen to extend only a short distance into the Scottish Highlands. In the southwest, however, the extrusions presumably linked with the Antrim basalt plateau[170]) and formed a fairly continuous field. The Antrim lavas, of a present total thickness of some 300 m, cover approximately 4,000 sq. km. They are built up of successive flows, divided by an "interbasaltic horizon" into *Lower Basalts* (olivine-basalts)[171]) and *Upper Basalts* (olivine-basalts[171]) in south Antrim, tholeiitic basalts in north Antrim, *e.g.* Giant's Causeway). All lavas are subaerial flows and the weathering on top of individual flows indicates minor periods of volcanic quiescence. The interbasaltic formations are thin layers of red bole[172]), of kaolinized basalt, or beds indicating kaolinization followed by laterization, *i.e.* by the formation of aluminous and ferruginous laterite (bauxite and iron ore). From the major inter-

[169]) T. N. George (1965, figs., 1.17 and 1.19).

[170]) J. K. Charlesworth and J. J. Hartley (1948).

[171]) The terms olivine-basalt and tholeiite have not proved to be entirely satisfactory, and according to C. E. Tilley (1950) the former is now referred to as *alkali basalt* type.

[172]) *Bole* is a bright-red, waxy or unctuous decomposition product of basaltic rocks, having the variable composition of lateritic clays (A. Holmes, 1920, The nomenclature of petrology).

basaltic horizon, bauxite and iron ore were mined for many years. The time interval represented by the well-marked interbasaltic horizon[173]) must be remarkable, the formation of the laterite alone may possibly approach a span of one million years[174]). The *interbasaltic period* apparently commenced with the outpouring of acid lavas (quartz-porphyries, rhyolitic pitchstone, obsidian). Rhyolitic debris was subsequently distributed over a very wide area of Lower Basalts. Kaolinization decomposed this debris and affected the underlying basalts to a depth of some 30 meters (formation of lithomarge). Through the laterization of the lithomarge bauxite and iron ore resulted.

The formation of residual tropic soils at 54° northern latitude is consistent with the distribution of older Tertiary floras in the Northern Hemisphere. In the submerged basins of western Europe many subtropical fossil plants are recorded. Particularly well-known is the Eocene *London Clay flora* described by E. M. REID and M. J. E. CHANDLER (1933). These authors have brought together critical evidence sustaining the assumption that—despite this warm climate in northern latitudes—the poles occupied their present position during the Eocene. Among paleobotanists[175]) there is agreement on the existence of latitudinal zoning on the northern continents during the early Tertiary. Subtropical, temperature, and cool-temperature zones[176]) can clearly be distinguished. As to the *London Clay flora* it is interesting to note that this was mainly of tropical rain-forest type, allied principally with the living Indo-Malayan flora. It apparently reached Britain by way of the shores of the Tethys Sea. This sea connection presumably carried the equatorial current[177]) of the Indian Ocean to the shores of western Europe's Eocene land masses.

The Antrim interbasaltic horizon encloses remains of subtropical plants which occur as lenses or pockets of *impure coal* (lignite). Locally

[173]) V. A. EYLES (1950).

[174]) The Antrim bauxites are up to 3 m in thickness.

[175]) E. W. BERRY (1930, R. W. CHANEY (1940, 1947), C. E. P. BROOKS (1949).

[176]) See map of Eocene '*isoflors*' by R. W. CHANEY (1940, p. 481).

[177]) In the London Clay flora, among numerous angiosperms whose modern equivalents live in the tropical rain-forest of Indo-Malaysia, the record of *Nipa* is one of the most significant. Now confined to tidal flats at low latitudes, this palm has been recorded southeastward from England across Europe and Asia, along the shore of the great Nummulitic or Tethys Sea. It is assumed that along this shore the London Clay and other floras migrated northward and westerly across India and the Near East to western Europe. In the London region *Nipa* was living at its northernmost range, since it is not known farther north.

As to the general distribution of the Paleotropical-Tertiary flora it should be emphasized that the Tethys Sea appears to have interposed a barrier to migration between the northern and southern hemispheres, resulting in Eocene and later differentiation of their vegetation (R. W. CHANEY, 1947).

the thin seam of lignite has been removed by erosion preceding the resumption of volcanic activity (outpouring of the Upper Basalts). In the Inner Hebrides beds of bole have been recorded too, but there are no deposits of iron ore or of bauxite like those of the Antrim plateau. Other interbasaltic sediments, however, including impure coal, leafbeds, sandstones, and conglomerates are frequent. A. GEIKIE found abundant evidence of *river-action* on the lava sheets of the Inner Hebrides. The composition of river-gravel reveals a partly distant transport from the Caledonian massifs to the east[178]). There is evidence also of the occurrence of *lakes* and the repeated *growth of forests* on the weathered lava sheets. Even trees remaining upright and apparently in place but drowned by lava floods have been observed[179]). *Ash beds*, however, are scarce all over the Scoto-Irish field.

In the Inner Hebrides, most of the exposed lavas are of alkali basalt type; tholeiitic flows at most places appear relatively late in the succession. This might suggest the formation of early alkali basalt magma by partial melting of sub-crustal material, followed by the rise of tholeiitic magma at local centers due to melting of a higher layer (L. R. WAGER, 1956). Yet, following G. W. TYRRELL's concept[180]), the eruption of the higher series of plateau lavas is considered to be the first event of the second episode in the Scoto-Irish volcanic history. Those lavas are closely associated with the development of calderas, ring-dikes, cone-sheets and plutonic intrusions.

Intrusive centers. — The main extrusions of basalt lavas were followed by another kind of volcanic activity. *Explosion-vents*, mainly due

[178]) A. GEIKIE regarded the outwash plains intercalated among the lava flows of the Inner Hebrides as derived from 'a river which, like the rivers that traverse the lava-deserts of Iceland, flowed perhaps in many separate channels across the basalt-fields . . . and was liable to have its course shifted from time to time by fresh volcanic eruptions. That this river came from the east or northeast and had its source among the Western Highlands of Inverness-shire, may be inferred from the nature of the stones which it has carried for 30 miles or more along its bed.' (1897, vol. 2, p. 229).

[179]) A classic example of a *lava-bedded* Tertiary *coniferous tree* has been described from the Ardtun section, western Mull by J. S. GARDNER (1887, p. 283):

'A large trunk of a coniferous tree, 5 feet in diameter, perhaps *Podocarpus*, has been enveloped, as it stood, in one of the flows of Trap to the height of 40 feet. Its solidity and girth evidently enabled it to resist the fire, but it had decayed before the next flow passed over it, for its trunk is a hollow cylinder filled with debris and lined with the charred wood. A limb of another, or perhaps the same, tree is in a fissure not far off. MACCULLOCH, who was certainly a most keen observer, did not overlook this tree, which he described in 1819 in his 'Western Isles of Scotland', vol. i, p. 368, pl. xxi, fig. 1. The trunk was thought to be in a vein of conglomerated fragments of Trap imbedded in a paste of the same. He had also ascertained the wood to be coniferous.'

[180]) G. W. TYRRELL (1949, table p. 419).

to the uprise of rhyolitic magma, occurred at various places along Scotland's present western sea-board and are again encountered in northeastern Ireland. The formation of vent complexes was followed and in some cases preceded by the *intrusion of plutonic masses.* Within several of these complexes, the center of activity shifted with time from one part of the area to another. In Skye, Ardnamurchan and Mull, for example, there are at least three successive centers at each complex. In some cases, ring intrusions are concentrically disposed about the individual foci. The plutonic masses which constitute the roots of volcanic structures, and which make up some of the larger rings, are *gabbros*, *granites* and *granophyres.* Some of the centers include *ultrabasic rocks* (allivalite, picrite, peridotite) which are believed to have been produced by an accumulative type of differentiation[181]). *Composite intrusions* are abundant. They generally show basic magma chilled against the country rock, and acid magma injected along the center of the basic mass or along planes of weakness near its contacts. Hybridization phenomena along the interior contacts are frequent.

By a process of *thermal metamorphism* at many places, sediments and other rocks adjoining Tertiary intrusive centers were thoroughly transformed. For example, near and in the gabbros of Skye and Ardnamurchan, older Tertiary basalt flows were transformed into pyroxene granulites; from Mull and Ardnamurchan hornfelses with spinel and corundum are known to have derived from bole and pelitic beds.

The main centers of Tertiary intrusive rocks are obviously confined to an alignment running south-southeasterly from Skye. This row and the close packing of its subparallel dolerite dike swarms suggest that in early Tertiary times crustal tension and magmatic invasion particularly concentrated along that belt. The igneous centers cut across any kind of geological structure. Yet they are localized at or near the *intersections* of the NNW–SSE alignment with the Paleozoic major faults: The centers of Skye, Rhum and Ardnamurchan occur close to the Moine Thrust; Mull is associated with the Great Glen Fault, and Arran with the Highland Boundary Fault. The Irish centers though lying some distance out of the major belt are located where the closely-folded Lower Paleozoic succession of the Southern Uplands and related faults find their continuation in the west.

The majority of acid Tertiary intrusive rocks yielded *isotopic* ages between 65 and 50 m.y. indicating Paleocene or Eocene as their time of emplacement (P. A. SABINE *et al.* 1965).

[181]) G. TYRRELL (1949, p. 422); G. M. BROWN (1956); L. R. WAGER *et al.* (1960); W. J. WADSWORTH (1961).

The dike swarms. — The later development of the igneous field is characterized by great swarms of dikes[182]). These are especially abundant in the vicinity of intrusive complexes, to which they are evidently related. Some centers have radial and tangential dike swarms, which normally do not extend far from these sites. Acid dikes and multiple basic dikes are restricted, indeed, to the surroundings of intrusive centers. The basic dikes, including both the olivine-dolerite suite or the contrasted group of tholeiite and quartz-dolerite, are found in all parts of the Scoto-Irish field. Yet most dikes are grouped in linear swarms with a dominantly NW–SE trend and extending for hundreds of kilometers. The major swarms of the Inner Hebrides emanating mainly from Skye and Mull run across all of southern Scotland and members can be traced into England as far as Durham and Yorkshire. Smaller swarms of similar trend cluster about the Irish centers Slieve Gullion and the Mournes.

The emplacement of dike swarms evidently involved a considerable effect of *crustal tension.* Computation on this phenomenon has been made for the centers Mull and Arran where dike swarms are extremely dense. In a distance of 20 km across the swarm on the southeast coast of Mull, 375 dikes have a cumulative thickness of 0.75 km, indicating a tensional effect of 30 to 40 meters per kilometer. For the example of Arran the calculated effect increases to close to 80 meters per kilometers. However, with regard to the *time* involved in this process the dike intrusions must have covered a very long period. Where ages of dikes relative to the emplacement of intrusive centers were examined, it turned out that the dike formation extended through much of the period of local activity, although it is true that many dikes clearly were intruded towards the close or after the formation of the plutonic bodies.

Structural events accompanying and succeeding igneous activity. — The gross feature of the Scoto-Irish igneous field is controlled by the prevalence of NNW–SSE alignments. Such a direction may first have been outlined by a sedimentary trough that was initiated in the early Mesozoic. The trend continues through the Faeroes and Iceland to Greenland. When basaltic eruptions started at the beginning of Tertiary times in the northern parts of the British Isles a block of nearly base-levelled land had emerged. The volcanic activity evidently was confined to this elevated country. In other word, the Scoto-Irish field was emplaced within a distinct continental rise of late Cretaceous to early Tertiary age. Since the floor upon which the flood basalts were poured out was a peneplaned landsurface, any subsequent distortion of this reference horizon is a measure of structural events in later Tertiary

[182]) E. M. Anderson (1951, pp. 43–48).

times. Indeed, the varied attitude of this marker indicates that the igneous field was repeatedly broken by faults, and was subjected to warping and arching. Impressive evidence of *late Tertiary erosion* is displayed in the Inner Hebrides. The faulted basalt plateau has been dissected into fragmentary outliers of residual summits. Volcanoes, marked by their local vents and hypabyssal intrusions, have been truncated to their roots. Plutonic masses which must have consolidated under sizable cover have been stripped. It is assumed that much the greater part of this differential erosion occurred prior to the Pleistocene glaciation. In both Scotland and Ireland relics of distinct platforms have been ascribed to stages of late Tertiary abrasion and base-levelling (J. E. RICHEY, 1961, p. 114).

As to the problem of the existence of a systematic form of what was earlier called "a zone of crustal weakness", referred to by others as the "Hebridean rift"[183]), T. N. GEORGE (1965, p. 33) concluded that such a form cannot be discerned in the tectonic pattern. Yet, he says, 'there can be no doubt that the initial highly varied topography of a volcanic landscape was further roughened and made more irregular by the imposition of folds and faults of such magnitude' (*l. c.*). Whatever the nature of this NNW–SSE trunk-line exactly may be, the following relationships stand: Its association with a trough of Mesozoic sedimentation, the parallelism of early Tertiary plutono-tectonics, and the striking alignment of dike swarms. This altogether indicates that the *pattern of regional stresses*[184])—the axis of least compressional stress being perpendicular to this NNW–SSE direction—remained the same throughout Mesozoic and Cenozoic times. This is also consistent with the trend of the shallow Tertiary folds in southern England which run roughly at right angles to the Hebridean alignment.

In terms of *physical geography*, the Hebridean "rift" reflects the hinge zone about which Britain's summit topography is tilted eastwards[185]).

4) The Islands in the Atlantic Ocean

The Greenlandic as well as the Brito-Irish fields bear the features of continental rises, including significant rupture patterns, when the vol-

[183]) The "*Hebridean rift*" is a conceptual structure, proposed *a priori* by H. CLOOS (1939, pp. 512–13).

[184]) E. M. ANDERSON (1951).

[185]) ... 'The meagre evidence available from the most elevated terrains of Britain suggests that two cycles of widespread Cainozoic planation have existed, the former possibly of extreme planation the latter broadly undulating. Both have been tilted eastward upon the flank of a broad cymatogenic arch the western aspect of which, across Ireland, may have been considerably flatter. But no evidence has emerged for dating these surfaces accurately.' (L. C. KING, 1962, p. 390).

canic activity set in. Both regions formed large plateaus of land, extensive lava plains covered in places by loose fragmental products. The latter originated through weathering of the scoriaceous surfaces of the lava flows and minor volcanic surface structures. Following the conclusions of L. HAWKES (1916, pp. 390–91) 'in all probability these plains connected the New and Old Worlds, but commonly there was a dearth of rivers, plants and animals, and no migration of these latter. At rare intervals vegetation gained a foothold, and "it is not improbable that the basalt plateau might even be densely wooded"[186)], though it is unlikely that this condition obtained over the 'land-bridge' in its entirety at any one time; it is more reasonable to conceive of temporary oases, limited in extent, themselves migratory.' This leads to the crucial problem of what was the structure and composition of the pre-basaltic pavement in the realm of the Atlantic Ocean. Was it a wide stretch of emerged land that was the site of lava outpourings or did the lava spread over the floor of what was then the North Atlantic? On the Atlantic islands, both Iceland and the Faeroes, unfortunately the lowermost basalt floods do not come to the surface at all. Based on *seismic studies* E. TRYGVASSON and M. BÅTH (1961) and G. PÁLMASON (1963) concluded that in Iceland the *base of the Tertiary lava pile* is situated some 2 to 3 km below sea-level. At places the lava may even lie as deep as 4 km. In the Faeroes G. PÁLMASON (1965) obtained similar results[187]). The basement supporting this volcanic load yields velocities intermediate between those of the typical granitic and gabbro layers. However, on both Iceland and the Faeroes the pile of Lower Tertiary basalt flows was subsequently subjected to warping, tilting and differential displacement. Due to the Upper Tertiary and Pleistocene distortion the stratigraphic columns exposed at the surface are 7–10 km thick in Iceland and more than 3 km in the Faeroes.

The Faeroes. This group of islands situated around the 62nd parallel consists almost exclusively of Tertiary lavas of a total visible thickness of close to 3,000 m. No traces of a non-basaltic substratum have been found either by heavy-mineral analyses of shore sands or by finding non-basaltic rock components among interbasaltic sedimentary strata. Neither vent-fillings nor agglomerate beds have yielded material that is not of basaltic origin. Based on recent field-research, A. NOE-NYGAARD, in his paper of 1962 on 'The geology of the Faeroes'[188]) distinguished

[186]) Quoted from J. GEIKIE (1883, p. 241).

[187]) In Strömö the base of the flood basalts was found to be at 2.5 to 3 km below sea-level in the north and 4 km in the south. In Syderö the suggested interface was at 2.5 to 3 km.

[188]) A complete list of earlier literature on the geology of the Faeroes, up to 1946, has been published by J. RASMUSSEN (1946).

three main divisions of lavas and one continuous horizon of interbasaltic sediments: (i) the *lower lava series* (900 m thick) includes some forty to fifty flow sheets, intercalated with thin beds of tuff including sporadic lenses of coal. Single flows can be traced for long distances. (ii) After an erosional interval, a *succession of sediments* was laid down. These beds of an average thickness of 10 m consist of hardened clays with local intercalations of sand, of pebble-beds, and include one workable *coal-seam.* A few poorly preserved plant-remains[189]) have been found. (iii) The period of sediment disposition was brought to an end by explosive volcanism which produced a layer of pyroclastics up to 100 m thick. Thin lava flows were intercalated in the upper part of this succession which passes upwards into the *middle lava series* (over 1,350 m thick). In contrast to the monotonous rock-type of the lower series, the middle series shows a variety of basalt-types, all of which are developed as ropy lavas with reddish surfaces. There are abundant amygdales filled with zeolites. The individual flows do not exceed 1 m in thickness, but are generally welded together to form compact masses. Vents, apparently having produced those flows, are now packed with agglomeratic material. These feeders are mainly found along a distinctive NW–SE fissure system (iv) The *upper lava series* (625 m thick) is made up of distinct flows intercalated by tuff beds similar to those of the lower lava series. At Kollefjord, a single fissure-eruption was found to have produced a volume of lava of 10 to 20 cubic kilometers.

There is evidence that the flows of all lava groups in the Faeroes were of *subaerial origin.* Yet from the upper lava series, A. NOE-NYGAARD (1939) reported sideromelane-bearing tuffs, indicative of rapid chilling. This is likely to be related with cold water either from lakes or from the sea.

Succeeding the period of surface volcanism minor *dolerite intrusions* settled into the interbasaltic sediment horizon, and were emplaced between the middle and upper lava groups. The Faeroes plateau is cut by hundreds of dykes; however, most are clustered in a belt running WSW–ENE across the northern group of islands.

The structure map of the Faeroes, compiled by A. NOE-NYGAARD (1962, pl. XVI) indicates a slight tilt of the whole plateau, generally towards the east. At the same time a very gentle folding is revealed. This warped the plateau about WSW–ENE axes, a direction outlined also by the present watershed of the northern island group.

The distortion of the plateau is referred to post-volcanic times; it may be the result of an uneven yielding of the pre-basaltic substratum.

[189]) According to J. RASMUSSEN (1963, p. 30) only two definable species of plant fossils have been found (*Sequoia langsdorfii* and *Taxodium distichum*). With reference to the Scoto-Irish field and to Iceland an Eocene-Oligocene age is suggested.

Related to the warping is a pattern of joints which clearly postdates the late dike formation. Since Pleistocene erosion was essentially guided by such joints it is suggested to refer their time of formation, that is the deformation of the basalt plateau, to the Late Tertiary.

Iceland. Covering an area of some 100,000 sq. km, the Tertiary and Quaternary volcanic rocks of Iceland represent the largest field of coherent outcrops in the Brito-Arctic province. The Tertiary plateau, originally built up by horizontal basalt floods, was subsequently moulded by faulting, tilting, by erosion and abrasion. The map pattern of Iceland's geology displays a bilateral symmetry, with a belt of Quaternary volcanic rocks crossing from north to southwest through the center of the island, and with remnants of the Tertiary plateau formations on either sides. The latter are generally inclined a few degrees towards the broad central zone of subsidence, referred to on previous pages as the 'central graben'. With regard to Iceland's volcano-tectonic position on the crest of the Mid-Atlantic Ridge effects of modern as well as Tertiary tensional tectonics have been discussed (cf. p. 179). Yet, Iceland is not the superelevated crest of the Atlantic rise. On the contrary, in its basic structure Iceland is part of the Faeroe-Iceland-Greenland Ridge all of which apparently sank in mid-Tertiary time. Structurally Iceland occupies an exclusive position, that is the intersection of the Mid-Atlantic Ridge and the Brito-Icelandic-Greenlandic belt. The magma-tectonic significance of such points of interference[190]) of large scale linear structures has been emphasized in particular by R. A. Sonder (1938, 1956). Indeed, Iceland's volcanic activity is unique; no other field produced an equivalent amount of volcanic rocks in historic times. 'The geology of Iceland has little to do with continental geology ... It has the earmarks of an oceanic island born out of the deep sea' wrote T. F. W. Barth in his monograph on the volcanic history of the island (1950, p. 3). He admitted,

[190]) '... *Lineare an Interferenzstellen mit querlaufenden Linearen* pyrogen aktiviert werden. Bei der Funktion des Linears als rhegmatische Gleitbahn müssen an Kreuzstellen von solchen intrakrustalen Gleitbahnen tektonische Komplikationen auftreten. Horizontale Verschiebungen an einem Linear stören und blockieren lokal die Gleitbahn des geschnittenen Linears. Soll letzteres wieder fahrbar werden, so werden Scheerungen, Spaltenlockerungen und tektonische Unruhe an der Kreuzungstelle erzeugt, welche Vorgänge nun ihrerseits den Aufstieg von Magma an diesen kritischen Stellen ermöglichen. Die meisten pyrogenen Aktivierungen ausserhalb der Orogene dürften einen derartigen Hintergrund haben, besonders dann, wenn die vulkanischen Zentren mehr oder weniger vereinzelt auftreten. Neben Einzelvulkanen findet man nicht-orogene Vulkangebiete, welche sich flächenartig ausdehnen. Dabei werden oft weite Flächen von basischen Lavafluten überdeckt. In diesen Fällen scheint das Krustenmosaik der Rinde sehr viele Leckstellen aufzuweisen, wobei im Detail manchmal parallele Spalten wie in *Island* oder parallele Vulkanstaffeln wie in Mittelamerika zu erkennen sind...' (R. A. Sonder, 1956, p. 120).

however, 'it cannot be denied that patches of sialic (continental) material may have existed beneath Iceland, this material has been assimilated by the inexhaustible masses of the suboceanic basalt magmas' (*l. c.*). Although these sentences quoted evidently contradict each other, they shed light on two central problems of Iceland's geologic past. First, was Iceland born out of the deep sea? Presumably not; all Tertiary lava floods exposed at the present surface indicate subaerial emplacement. Seismic evidence suggests that they are underlain by another pile of lavas, at least some 2,000 m thick. The seismic layering of Iceland's volcanic upper crust, however, is irregular. From the Reykjavik–Tjörnes section, E. TRYGGVASON and M. BÅTH (1961) concluded that in the neovolcanic central zone the lava pile is less thick than below the exposed Tertiary plateau block. The decreased thickness found in the central zone was related to a physical mixture of the Tertiary lava pile and deep-seated magma. Whatever the original thickness of the Tertiary basalt plateau might have been, it is unknown whether those lavas, now submerged below sea-level, once were spread over a land-surface or extruded in the form of submarine flows. With regard to the considerable down-flexuring of the basalt plateau south of Scoresby Sund, situated only some 450 km northwest of Iceland, it would be likely that in a similar way the early flows of the Icelandic pile were extruded above or close to sea-level. Having reached this conclusion, we are urged to visualize the kind of crust which made up that land complex or shallow block in the realm of the late Mesozoic Atlantic. This, in turn, immediately leads to the second problem, that is Iceland's residual sialic basement. This is a delicate and complex problem; it is important not to be too hasty in reaching a conclusion since Iceland may yield—according to preliminary results hitherto obtained—an outstanding example of a large continental crustal block that has been decisively transformed by Upper Mantle processes[191]). The problem has been approached along

[191]) The problem of removal of crustal material from below and the transformation of acid rock material into basic types (*basification* or '*basaltization*', V. V. BELOUSSOV, 1962, p. 682) bears much on the conversion of continental fractions to geosynclinal or oceanic basins (K. J. HSU, 1965). About the nature of this process evoking removal of the crust from below, indeed, various speculations have been made. For example, J. GILLULY (1955, 1963) postulated '*subcrustal erosion*' by convection currents in the Upper Mantle. G. C. KENNEDY (1959) considered a '*phase change*' which converts crustal material to mantle material, thereby rising the Mohorovičič-discontinuity and thinning the crust. Yet, it appears insufficient to explain the Moho as a phase boundary between gabbro and eclogite that may move up and down according to variations in pressure and temperature. There is objection to this concept because the removal of crustal material from below evidently may affect both the 'basaltic' as well as the 'granitic' layers of the crust. Attention was also called to the fact that 'some evidence exist which indicate that the 'basaltic layer' of the seismologists may be well composed mostly not by basic rocks but by

two separate lines, by *geophysical* and *petrochemical methods.* As to the first method of investigation it is self-evident that any geophysical sounding on the pre-Tertiary substratum deals with faint relics only, due to the fact that the area concerned was the site of an overwhelming igneous activity in the early Tertiary and from Pliocene to recent times. No wonder, then, that the seismic properties of this substratum are puzzling, that is to say they were found to be intermediate between those of "granite" and "gabbro" layers. Further seismic, gravimetric, and magnetic studies will certainly improve our knowledge on the present structure and physical status of the area concerned. Yet as to the process of postulated crustal transformation, we have to search for remainders from the past. This is the approach though the petrochemistry of the Tertiary volcanics and intrusives. Among them, of course, Iceland's acid igneous rocks play an important rôle. As to the overall characteristic of the Icelandic eruptive field, T. F. W. BARTH (1962, p. 179) concluded: 'Petrographically it is transitional into a continental province, although placed in the Mid-Ocean. It is overwhelmingly basaltic but not alkalic, the residual differentiation products being liparitic [a synonym for rhyolite]; nepheline-bearing lavas do not exist.' *Rhyolitic tuffs*[192]) have been reported from the eastern plateau of Tertiary basalts. They were probably related to intrusive masses[193]), including felsite, granophyre, granite, and granodiorite, found in the same region. Other intrusives are gabbro, but rocks of intermediate composition are strikingly scarce. Most of the intrusions, however, are composite types, made up of gabbro, granite and granophyre. The origin of this acid Tertiary rock material is considered as the crucial point. Arguments have been brought forward, however, in favor of both magmatogenic explanations, either the acid magmas originated from differentiation and fractionation of sub-crustal basaltic magma, or they were formed by remelting of or contamination with ancient crustal material. Any pursuance of this

metamorphic rocks of granulitic facies. The formation of such facies is the result of *degranitisation* which is complementary to the process of granitization occurring in higher layers of the crust at the level of the amphibolite metamorphic facies. If this idea is true, the deep erosion of the crust cannot be explained by the phase-transition. One may better think of some kind of deep ultrabasic metasomatism. But since such ultrabasic metasomatism is exhibited only on a minor scale near the surface, and only very few extrapolations would allow us to suppose that the same process may develop in depth on much greater scale, this problem remains a puzzle so far' (V. V. BELOUSSOV, 1965, p. 83).

Stimulating results on marked differences between the crustal structure in various geotectonic zones—including *Iceland*—have been reported by I. A. REZANOV (1965).

[192]) T. TRYGGVASON and D. E. WHITE (1955) G. P. L. WALKER (1958).

[193]) H. K. CARGILL *et al.* (1928), J. JÓNSSON (1954), G. P. L. WALKER (1963).

discussion, of course, is made on the premise that magmatic differentiation on the large scale is a geologic fact. Yet, having agreed to this, one may question with G. P. L. WALKER (1963) whether such large amounts of acid magma[194]) seem likely at all to have originated by crystal fractionation of basaltic parental magma. A clue to this problem is seen in isotope investigations. Preliminary results on Sr^{87}/Sr^{86} ratios of Icelandic rocks and their relationship to data from Scotland (Isle of Skye) and East Greenland (Skaergaard intrusion) have been discussed by S. MOORBATH and G. P. L. WALKER (1965).

Tertiary volcanism and tectonics. — A geologic map of Iceland including an outline of the Tertiary sequence of predominantly basaltic lavas was first published by T. THORODDSEN (1906). For centuries it was well known to the inhabitants of Iceland that seams of coal, carbonized trunks and even trees in place are encountered in partings between basalt sheets. Those remains of trees were ascribed to *Surtarbrandur*, *i.e.* a catastrophic fire in primeval times caused by *Surtur*[195]), the giant of fire. Originally the term has been used only for relics of trees in coal-bearing strata. T. THORODDSEN (*op. cit.*) and later authors applied the term to all Tertiary[196]) lignite occurrences in Iceland. Indeed, thin sedimentary partings, mainly tuff beds, are abundant all over the plateau formation. In the Northwestern Peninsula, these interbeds, partly of multicolored clay, are thicker and rich in remains of terrestrial fossil plants (including localities at *Steingrimsfjördur* (*Tröllatunga*), *Brjánslaekur* and others). OSWALD HEER attributed to this Tertiary flora of Iceland 'Miocene' age, as he did with the other northern Tertiary floras which subsequently have proved to be of early Tertiary age. M. SCHWARZBACH (1955, p. 103) emphasized that the datings based on plant macrofossils were not accurate enough; he indicated the age of the interbasaltic flora of Northwestern Peninsula as *Lower Tertiary* (tolerating Eocene to Miocene). Pollen and spores from these beds have been reported by J. ÁSKELSSON[197]) and then extensively investigated by H. D. PFLUG (1956, 1959), M. SCHWARZBACH and H. D. PFLUG (1957) and S. MANUM (1962). The age of the *Tröllatunga* microfossil assemblages was suggested to be *Upper Paleocene to Lower Oligocene.* S. MANUM (*op. cit.*) concluded

[194]) In eastern Iceland, acid volcanic rocks comprise about 10 per cent of the Tertiary lava pile. They are confined, however, to central volcanoes, and make up some 20 per cent of the bulk of these volcanoes, with andesites comprising perhaps another 10 per cent (G. P. L. WALKER, 1963, p. 57).

[195]) In Old Norse mythology Surtur is the name of the black giant of fire, the governor of volcanoes and lavas. Hence Iceland's largest cave has been called "Surtshellir", and again, the island "Surtsey" erupted in 1963, is the island of Surtur.

[196]) Eocene-Miocene as well as Pliocene coal-bearing strata (Dr. S. THORARINSSON, private communication).

[197]) Papers of 1947, 1954, 1956 written in Icelandic.

that the Lower Tertiary floras of Iceland, Greenland, Spitsbergen, and Ellesmere Island were not identical, but were composed to a considerable degree of the same families and genera.

On the basis of pollen flora and *interbasaltic "tillite" beds* found in southeastern Iceland, a *pre-Pliocene glaciation*[198]) was suspected by J. JÓNSSON (1954, 1955) and SCHWARZBACH and PFLUG (1957, pp. 295–96).

The building up of the vast Icelandic lava plateau was apparently completed by Oligocene (?) or Miocene times. At that time, the pile of lava—hitherto a structurally uniform mass—was subjected to faulting, differential vertical displacement, and considerable erosion. This *major tectonic event* (of pre-Pliocene age) resulted in a decomposition of the plateau into tilted blocks of varied size[199]). The large blocks show tilting of a few degrees only while in smaller blocks the basalt sheets may dip up to 30°. At the close or after this major tectonic event, according to T. EINARSSON (1960, p. 15), onyxes[200]) and other infillings of vesicles, joints and fractures were deposited. Onyxes are frequently encountered in the deeper part of the Tertiary lava pile. Their plane-parallel layers—formed in a horizontal position—show still a near-horizontality, while the host lava sheets dip more steeply[201]). It was therefore concluded that after the formation of these subcrystalline silica infillings only very slight additional tilting took place. There was later vertical displacement but hardly any tilting. In eastern Iceland, the faulting is believed to be later than the emplacement of dike swarms; those intrusives as well as the rocks of the central volcanoes were seemingly involved in the tilting.

Following this major disturbance a *long period of erosion* reduced the volcanic block mountains to a base-levelled lowland. At that time, from the rising edges of tilted blocks in particular, considerable sections of the Lower Tertiary lava pile were removed. L. HAWKES (1938, p. 293) considered this profound and level erosional surface, that was 'produced

[198]) It is interesting to note that L. R. WAGER, based on a different kind of evidence, saw the commencement of the Greenland ice sheet in Miocene times (cf. footnote p. 196).

[199]) See map showing dip of basalts in Iceland, published by T. EINARSSON (1960, p. 13).

[200]) The term *onyx* is applied to banded chalcedonic quartz, in which the bands are straight and parallel, rather than curved, as in agate. The main type of onyx referred to above is white and white-grey and occurs in the lower part of the Tertiary lava plateau. There is, however, another type which occurs in younger lavas and at high elevations in the plateau. This is of a dull yellow-grey color and imperfectly stratified. It was probably formed in colder water than the normal type and may contain iron. Late-Pleistocene or younger rocks contain as a rule no infillings.

[201]) According to T. EINARSSON (*l.c.*) the layers of the onyxes may dip 1–2° while the sheet of flood basalt dips 6–8°, the dip being in the same direction. Only in a few cases have onyxes been seen dipping as much as 3–4°.

after considerable tectonic disturbance', as the decisive element of the present topography of the upland regions, at least in northern Iceland. T. EINARSSON (1960) agreed to this and declared this *Tertiary*[202]) *peneplain* as the "1st stage" in the morphological development of the Icelandic plateau regions. The peneplain was subsequently elevated and in a subdued relief the valley sites were deepened.

It was apparently in *Pliocene* times that *tectonic activity* revived and Iceland's modern volcanism commenced. The island was affected by differential vertical displacement that resulted in high plateaus on both sides of the 'central graben' which then was initiated. This depression, however, is a compound structure made of various subsided fault-blocks rather than a simple rift valley[203]). It is not easy to reveal the history of this subsided central zone since the Pliocene to recent volcanic cover sealed all of the older pavement. It is only in the North Iceland depression that the basal basalt pile comes to surface. At the *Tjörnes* peninsula, a 450 m thick succession of sediments, including both fresh-water and *marine* beds, rests on the eroded and tilted surface of older basalts. Coal-bearing strata are frequent. In non-marine sandstone also silicified and petrified tree trunks[204]) were found. It had been commonly accepted that these "*Tjörnes sediments*" were of Pliocene age (Crag). More recent investigations, however, seem to indicate that at least the uppermost group (*Cardium groenlandicum* zone) would be better dated as *Lower Pleistocene* (J. ÁSKELSSON, 1960, pp. 28–29). In southern Iceland, the 'central zone' comprises two distinct depressions, both having received a great amount of neovolcanic filling. The buried surface of the old plateau must here lie at a position below sea-level. All over the 'central zone' faulting, tilting, and formation of fissures lasted until the present time. As to the structural relationship between the subsided, neovolcanic median zone and the distorted Lower Tertiary basalt plateau, T. EINARSSON (1960, p. 18) emphasized that the main tilting observed in the pile of flood basalts is much older than the formation of the central depression (Pliocene to recent).

Younger volcanism[205]). — In the structural depression of North Iceland neovolcanic activity apparently commenced before the deposition of the "Tjörnes succession". Volcanicity continued through all of

[202]) 'The preparation of the upland peneplane and its deep dissection is a geological work of such magnitude that its commencement may well be assigned to the end of the Eocene or Oligocene periods,' thought L. HAWKES (1938, p. 293).

[203]) M. G. RUTTEN and H. WENSINK (1960).

[204]) G. G. BÁRÐARSON (1925), E. SCHÖNFELD (1956).

[205]) The reader is referred to the comprehensive papers by TH. THORODDSON (1925), T. F.W. BARTH (1950), and to the more recent summary papers by J. ÁSKELSSON *et al.* (1960).

the Pleistocene up to the present. During much of this time Iceland carried large sheets of ice. Yet during the last period of Pleistocene glaciation the continuous inland ice left some free nunatak regions in northwestern, northern, and eastern Iceland. The neovolcanic 'central zone' however, was heavily glaciated. Vatnajökull[206])—an ice sheet still over 1,000 meters thick—is a remarkable relic from that time. Consequently many Pleistocene and to some extent also recent volcanic formations were extruded beneath the ice. These rocks are known as the "*Palagonite Formation*"[207]) (called "*Móberg Formation*"[208])) by the Icelanders. H. Pjetursson (1900) was the first to demonstrate that this highly varied group of tuff and breccias includes also tillites and other glacial elements, indicating *Pleistocene* age. The petrological aspect of these particular volcanic rocks was mainly investigated by M. A. Peacock (1926a, b). As to the mode of emplacement N. Nielsen and A. Noe-Nygaard (1936, p. 122) distinguished two types of depositional environment: (i) accumulations in the vicinity of ice sheets (tillites and associated rocks, such as 'solifluctional breccias') and volcanic material erupted subglacially, (ii) accumulations in ice-free land-surfaces (interglacial lavas, pyroclastics and detrital sediments). The modern subglacial volcanoes of Iceland make it still possible, to study palagonitization *in statu nascendi.* Recent eruptions beneath Vatnajökull have been investigated by N. Nielsen (1937) and A. Noe-Nygaard (1940b). G. Kjartansson (1960) defined the "Móberg Formation" *sensu lato* as a complex of rock series ranging in age from the Upper Tertiary to the end of the last Pleistocene glaciation. In addition to traces of glacial environment and to fossiliferous beds representing interglacial stages, he considered also the magnetic polarity grouping[209]) of volcanic series. Following this concept, the "Móberg Formation" is made up of three different facies types which are not necessarily time-stratigraphic units.

(i) *Old Grey Basalts*: lava sheets differing from the Lower Tertiary plateau basalts by having lighter color and coarser texture. Intercalations of

[206]) *Vatnajökull* is the largest and highest (up to 2,119 m) ice sheet of Iceland; it is also the largest and most active glacier system in Europe.

[207]) *Palagonite*, a term derived from Palagonia, Sicily, and introduced by the volcanologist R. Sartorius von Waltershausen, who visited Iceland in company with the chemist, Prof. R. Bunsen, in 1846.

Palagonite is a yellow or orange, isotropic mineraloid formed by hydration and other alterations of *sideromelan* (von Waltershausen's term for basaltic glass), and constituting a characteristic part of palagonite tuffs. Two varieties, *gel-palagonite* and *fibro-palagonite* have been recognized by M. A. Peacock (1926 b), who reviewed the conditions which promote 'palagonization'.

[208]) Icel. *móberg* = "brown rock".

[209]) Corresponding to periods of normal and reverse polarity of the earth's magnetic field (cf. T. Einarsson, 1960, p. 12).

clastic rocks make up about half of this facies. (ii) *Móberg sensu stricto*: areas chiefly consisting of brownish basaltic glass that has undergone palagonitization. The topography of the móberg areas is characterized by two distinct types of mountains: *ridges* whose alignment is controlled by fault and fissure patterns and *tablemountains*, small circular to subrectangular plateaus with steep sides. There is a controversy whether horst structures or differential erosion were the prime cause of the typical Móberg landscape. (iii) *Young Grey Basalts*, lava flows referred to the last interglacial; they are younger than the main features of the present topography. Yet they are ice striated and form roches moutonnées. By this they are distinguished from the recent lava flows.

The Pleistocene volcanism has continued without any interruption but within gradually limited areas during postglacial times[210]). By far the largest neovolcanic area is the 'central zone'. Next in size are the areas around Snaefellsjökull (western Iceland) and Öraefajökull (southeastern Iceland). Together these three areas cover some 35,000 sq.km. Within them there are 150–200 postglacial volcanoes (cf. Plate XLV). Of these volcanoes at least 30 have been active since the Vikings settled in Iceland, and more than 120 eruptions have been recorded within these 1,100 years. The postglacial *lavas*[211]) cover some 12,000 sq.km which is nearly one third of the neovolcanic areas. The production of *tephra*[212]) has also been considerable [213]). According to S. THORARINSSON (1960b) by far the greatest number of layers are *basaltic* and black. Calculated by volume, however, at least 20 per cent of the total postglacial tephra-production is *rhyolitic*, and the rhyolitic layers are the most extensive in the country. All the big stratovolcanoes in Iceland had one or more acid explosive outbursts. It seems likely that these

[210]) S. THORARINSSON (1960 a, p. 33) mentioned that 'in the subglacial Námafjall ridge east of Myvatn, which is built up subglacially by parallel running fissures one can directly follow the gradual change from wholly subglacial eruptions, producing palagonite-tuff breccias and pillow lavas via fissure eruptions which broke through the gradually thinning ice cover, to wholly subaerial, lavaproducing crater rows.'

[211]) The postglacial lava flows are predominantly basaltic in composition (cf. TH. THORODDSEN, 1905, p. 139).

[212]) S. THORARINSSON suggested the collective term '*tephra*', first used by ARISTOTLE, for *fragmentary materials* torn off and ejected in solid or molten condition by the erupting gases. With this he restricted the term 'tuff' to secondarily compacted fragmentary materials. The general term *pyroclastics* or *pyroclastic sediments* includes both tephra and tuff.

[213]) S. THORARINSSON (1960 b, p. 55) held that the total number of postglacial tephralayers in Iceland exceeds one thousand; many of them, however, are of a very limited extension.

volcanoes were supplied by individual magma pockets at a rather shallow depth and that there a process of differentiation took place during the intervals of quiescence. Tephrochronological studies of the activity of *Hekla* indicate a cyclic process, each cycle starting after a long period of quiescence with an acid initial-eruption.

Thermal activity. — Iceland's modern volcanism is accompanied by an intense thermal activity which has no connection with the Tertiary volcanism, although many of the existing *hot springs* occur outside the areas of neovolcanism. They are most numerous in the western part of the island, in particular in the Hengill-Ölfus area, about 50 km southeast of Reykjavik. Intermittent hot springs discharging explosively have been known for centuries in Iceland. They were called *geysers* after "Geysir" (*i.e.* the "Gusher" or "Spouter") which is the most spectacular of a group of geysers situated some 90 km east of Reykjavik. The available data on Iceland's principal hot springs and geysers were summarized by T. W. F. Barth (1950), G. Bodvarsson (1960) and G. A. Waring *et al.* (1965).

With regard to the entire Brito-Arctic igneous province it is evident that thermal activity is almost exclusively confined to Iceland and Jan Mayen, that is to the site of the Mid-Atlantic Ridge. It is worthwhile to note that no thermal activity occurs in the Scoto-Irish field[214]) nor in the Faeroes[215]). Outside Iceland and Jan Mayen, *East Greenland* is the only field where two localities[216]) of emerging thermal springs have been discovered.

[214]) In the British Isles, the northernmost thermal spring (28°C) emerges at Buxton, a bathing resort some 30 km southeast of Manchester (see G. A. Waring *et al.*, 1965).

[215]) The so-called "Varmakelda", a tepid spring (20°C) on the east coast of Österö, the only one of its kind in the Faeroes, is not of volcanic origin (A. Noe-Nygaard, 1942, Naturens Verden, pp. 39–42, Copenhagen).

[216]) Thermal springs have been found on either side of the mouth of Scoresby Sund. The southern locality is situated at the south side of "Henry Peninsula" (*Henry Land*, 69°35′ N) and was described by O. Nordenskjöld (1907, p. 221) as a 'hot spring' with a temperature of **38**°C, 'expelling a quantity of vapours' and containing 'sulphuretted hydrogen'. The well 'is strongly marked by the rich green algal vegetation'.

The northern locality refers to the vicinity of the colony Scoresbysund, where A. Pedersen (1926) discovered thermal springs at three places, namely in the neighborhood of the settlement *Kap Tobin* (70°25′ N), in a place some distance farther north, and in the vicinity of *Kap Hope* (70°27′ N). The temperature of water varies at these places. At Kap Tobin **62**°C has been registered, but at Kap Hope the temperature is considerably lower. From the Kap Tobin spring *sulphurite* and *siliceous sinter* are reported, although the principal chemical constituents are *Na* and *Cl*.

As to the springs near Kap Hope, A. Rosenkrantz (1929, p. 150; 1942, p. 54, pl. 4) ascertained that they emerge along a fault which separates Mesozoic sediments from Caledonian gneisses.

Jan Mayen. Jan Mayen is situated some 650 km north of Iceland on the continuation of the Mid-Atlantic Ridge. It is of considerable scientific interest on account of its isolated position in the midst of the Scandic Sea, and its geologically recent origin. In the 1920's the Norwegian Government established a permanent weather station and proclaimed sovereignty over the island. It is an inhospitable place, however, exposed to the hazards of climate and heavy sea. A bibliography on the history and scientific exploration of the island has been published by A. K. ORVIN (1960).

The island is 53 km long by 3 to 17 km wide, with its long axis oriented northeast. Its rock material[217]) is entirely *volcanic* in origin, basaltic lavas and tuffs of *Quaternary* age. The present-day island is part of a large volcanic edifice that includes the submerged Jan Mayen Bank south of the island. The whole structure—dominated by the great cone of the volcano Beerenberg[218])—apparently was built up on the flanks of submarine rift mountains[219]). Beerenberg is one of the world's most spectacular volcanic mountains. It rises directly from the deep ocean to a height of 2,277 meters above sea-level. The base of the mountain is formed by a broad dome of basaltic lavas rising gently to an altitude of some 1,500 meters. Sitting astride the dome is the summit lava cone with 45° slopes, some five kilometers in diameter and 750 meters high. The flanks of the basalt dome have been severely cliffed by marine erosion. The summit cone is heavily glaciated[220]), and on the northern side glaciers reach the sea. The building up of this sizable mountain obviously represents the latest major manifestation of volcanism in Jan Mayen. J. M. WORDIE (1926) considered Beerenberg to be of post-Pleistocene age. He felt that the extremely fresh topographic appearance of the summit cone strikingly contrasts the 'early maturity in the topography' of the much lower southwestern part of the island (Sör-Jan)[221]). He suggested therefore that those sections were older and that the volcanic activity on Jan Mayen had moved north-eastwards with time. The last eruption reported is that observed by WILLIAM

[217]) G.W. TYRRELL (1926), G. D. NICHOLLS (1955), H. CARSTENS (1962), F. J. FITCH (1964).

[218]) The name "*Beerenberg*", meaning Bear Mountain, was first used by Dutchmen in the 17th century. Polar bears occasionally are stranded at the island by the seasonal recession of the East Greenland drift ice.

[219]) B. C. HEEZEN and M. EWING (1961, p. 629).

[220]) D. J. J. KINSMAN and J.W. SHEAD (1963). The Glaciers of Jan Mayen, pp. 439–48, 5 figs., J. Glaciology **4**, 34, (Cambridge).

[221]) *Sör-Jan* (South Jan) is essentially a long pile of horizontal to slightly inclined basalt flows with many small volcanic cones aligned parallel to its length (cf. A. T. J. DOLLAR and D. M. BOYD, 1951, Trans. Geol. Soc. Glasg. **21**, p. 380, Glasgow; A. T. J. DOLLAR, 1965, Proc. Geol. Soc. London **1621**, p. 63, London).

SCORESBY, Jr., in 1818. There is no lava emission or explosive activity at present, but further eruptions might well occur. Hot steam and carbon dioxide are still being emitted from a young explosion cone (Eggøya), and earthquakes are common.

Based on a distinctive basaltic *tillite* occurring down low in the volcanic succession, F. J. FITCH (1964) concluded a late-Pleistocene age for the building up the Beerenberg basal dome and a post-Pleistocene age for the summit cone. Although no definite date for the birth of Beerenberg can be given, to FITCH it seems 'very probable that the migration of the principal volcanic focus of Jan Mayen towards the north-east occurred in the *late-Tertiary*' (*op. cit.*, p. 157). The side-stepping is thought to be related to 'wedging by magmatic pressure' and to an 'important transverse fracture' in the submarine rift pattern (*op. cit.*, p. 161). The older volcanic edifice, which had been reduced to low relief, is mainly represented today by the Jan Mayen Bank. From xenoliths brought to the surface by subsequent fissure controlled volcanic activity it was concluded that the basement of Jan Mayen includes volcanic centers which passed through the entire life-cycle of an oceanic basalt volcano.

As to the morphological evolution of Jan Mayen it is interesting to note that the submarine topography off the east coast suggests a submerged coastline of cliffs cut by glacial notches, similar to the present coast, but with the sea-level some 150 meters lower.

5) Submarine ridges.

At the present time, the 500 m depth contour line extends almost completely from Europe to Greenland across the *Faeroe – Iceland – Greenland Ridge*[222]). Depths are slightly greater in two small gaps, one near the Faeroes and another in the Danmarks Strædet (cf. Plate XLV). The geophysical characteristics of this transatlantic threshold differ from those attributed to oceanic rises (see p. 178). Apart from Iceland, the threshold is the site of neither seismicity nor volcanic activity. This, in addition to the geological history of Iceland and the Faeroes, places

[222]) Unfortunately there exists no general term to designate the submarine threshold which connects the Hebrides with Greenland through Iceland. It is true that in papers dealing with the geology of the Brito-Arctic Province, the name *Wyville Thomson Ridge* has been applied (G.W. TYRRELL, 1937, p. 98; C. E. WEGMANN, 1948, p. 18, pl. 1; E. WENK, 1961 a, p. 278; *etc.*). Yet, from the viewpoint of oceanic geography each section is treated singularly (T. STOCKS, 1950). There are thus three units: the *Greenland-Iceland Rise* and the *Iceland-Faeroe Rise* east and west of Iceland and the *Wyville Thomson Ridge* which stands as a barrier in the narrow Faeroe Channel. (Sir CHARLES WYVILLE THOMSON, a pioneer of deep-sea research, was the leader of the famous "Challenger"-Expedition 1872–76. He predicted the existence of a barrier in the Faeroe Channel on the basis of remarkable changes in temperature and fauna).

the making of this remarkable physiographic feature into Tertiary time. From conclusions reached on previous pages it seems likely that the Faeroe-Iceland-Greenland Ridge represents the drowned wreck of a collapsed early Tertiary rise that has been heavily loaded with surface volcanics. The stratigraphic records of Greenland and the British Isles refer the emergence of this rise to Upper-Cretaceous—earliest Tertiary times, *i.e.* prior to the major outpourings of lava floods. At both the East Greenland and the Scoto-Irish fields the early Tertiary surface volcanism buried a dry land area that had earlier been part of a shallow late Mesozoic Atlantic Ocean. Unfortunately there is no information on the nature of the base of the Tertiary lava pile, that forms almost all of the transatlantic threshold, including the Faeroes and Iceland. Yet there is the possibility that in the interregnum between the Mesozoic and Cenozoic a considerable area of land in the North Atlantic emerged as well. Whether this happened indeed or whether Iceland and the Faeroes were 'borne out of the sea' cannot be answered by sophistic arguments. The only reliable answer would come from core samples of drill holes showing the nature of the buried lavas and sedimentary interbeds.

In West and East Greenland, the building up of the extensive and very thick Eocene lava plateaus was accompanied by a gentle subsidence of the loaded areas. It is assumed that the lava outpourings never occurred very high above sea-level. This conclusions applies to the lava piles of Iceland and the Faeroes as well, and, hence, *gentle subsidence contemporaneous with surface volcanism* is suggested here too.

From the coastal structure of East Greenland we learned that after the middle or late Eocene (cf. p. 195) the basalt plateau south of Scoresby Sund was bent into a conspicuous flexure. In the region of Kangerdlugssuaq this caused a *relative vertical displacement of land and sea areas* amounting to some 8 kilometers. This giant coastal flexure is the structural link between the continental basalt plateau in East Greenland and its postulated drowned extension, in the Danmarks Strædet. Post-basaltic displacements, although of smaller magnitude, affected the Scoto-Irish field as well. On Iceland and the Faeroes the Tertiary lava piles are warped, faulted and tilted. Moreover, marine Pliocene and Pleistocene beds found on Iceland indicate that parts of this island, submerged at times, were raised again. Apart from a minority of such incontestable signs of **Cenozoic vertical displacement** there are many physiographically remarkable features still awaiting explanation. I cannot mention them all, yet it will be useful to review briefly some of the evidence of relative sea-level changes in the Scandic region.

One problem, as yet unsolved although discussed at length by Scandinavian authors, is that of the *strandflat*—a term introduced by

H. REUSCH (1894) for the low, rocky foreland along Norway's Atlantic coast. The strandflat—partly below, partly above water—is a sort of coastal platform, which varies from a few kilometers to 60 kilometers in width. This 'coast plain', however, has a rather uneven surface including a belt of innumerable low islands, skerries and rocks. It separates the high coastal mountains from the open sea. Channels crossing the strandflat are obviously related to the course of present fjord valleys. In cross-section these channels look like glacial valleys; their depth is several hundred meters but never approaches that of the overdeepened inner fjord basins (*e.g.* Sognefjord, – 1,200 m). In an outstanding paper of 1904, F. NANSEN dealt with the physiography of continental shelves around the Scandic Sea. In discussing the origin of submarine valleys, in particular those related to the fjords of Norway, he emphasized the osciallation *of the relative sea-level.* He thought that the strandflat channels were drowned river-valleys[223]), 'sculptured after the formation of the continental shelves, and that consequently the latter have been dry land' during longer periods in pre-glacial times (*op. cit.*, p. 192). In the Pleistocene, he suspected (*op. cit.* p. 166) 'the submerged valleys of the shelf have probably several times been more or less re-opened by glaciers', which have deepened and widened them. As to the formation of the 'drowned' valley troughs, thus, NANSEN (*op. cit.*, pp. 162 *et sqq.*) considered both a base-level of subaerial erosion, which required a considerable *elevation of the shelf*, and submarine glacial erosion. NANSEN's synthesis of the physiographic evolution of Norway's shelf challenged further investigation. It was argued by H. AHLMANN (1919, p. 209) that 'the bottoms of the submarine fjords are not situated at such a uniform depth that we can speak of one uniform base-level'. Yet, AHLMANN agreed that the coastal platform was once higher than now. He suggested a 250–300 m elevation of the shelf in the Pleistocene as opposed to NANSEN's estimate of a Pliocene elevation of 400–500 m. In a later paper, dealing in particular with the "strandflat problem", NANSEN (1921)

[223]) When only a few *submarine channels* were known, *e.g.* the submarine Hudson River Channel (J. D. DANA, 1890), geologists did not hesitate to ascribe them to the drowning of river valleys. Yet when echo-sounding had increased the reported number of great submarine valleys to approximately one hundred, R. A. DALY (1936, p. 401) felt that 'no published explanation of these "canyons" by subaerial river-cutting seems adequate'. He suggested turbidity currents as a major agent and thought that the cutting of the canyons took place during the Pleistocene when the sea-level was lowered by glacio-eustasy. The validity of this hypothesis has been discussed repeatedly. Modern investigators emphasize the importance of erosional processes by slumping action at the canyon heads. Moreover, as to the age of the cutting F. P. SHEPARD (1963, p. 504) concluded, 'whether we believe in a turbidity-current origin or not, it is far easier to explain the canyons as older than Pleistocene'.

came to emphasize the importance of '*shore erosion by frost*'. In his opinion this is a process of abrasion (marine erosion) strongly helped by the frost action (freeze and thaw). The fact that strandflats are common to shores of polar and sub-polar lands supports his assumption that Quaternary glaciation was involved. Comparative studies carried out in Antarctica led O. HOLTEDAHL (1929) to the conclusion that 'the existence of the *foreland glacier ice* ... and not the marine abrasion (assisted by the freeze and thaw action at the shore line) seems to explain the feature under discussion' (*op. cit.*, p. 16). As to Norway's coastal feature HOLTEDAHL thought 'that the present strandflat belt was cut by fjords *before* it was levelled' (*op. cit.*, p. 146), although he admitted that 'it may in general be very difficult, when we are dealing with a relatively deep channel in a region of strandflat character bordering on a high land area, to tell with certainty which is the oldest morphological element: the channel or the more or less plateau-formed surface' (*l. c.*).

Indeed, since NANSEN (1904) described the 'bathymetrical features of the North Polar Seas' the *importance of Cenozoic tectonics on the geomorphology of Fennoscandia* in particular and the peri-Scandic land areas in general has been emphasized by a number of writers. The early view that the Scandinavian mountain belt represents the remains of a supertowered Caledonian range has long been abandoned. The present concept is that the great height of the land is the result of a relatively recent, *i. e.* Tertiary, uplift. H. REUSCH (1901) was among the first to postulate the existence of an old, originally low-lying '*palaeic*' land surface[224]) which was raised and then exposed to vigorous erosion resulting in Norway's impressive fjord landscape. At the International Geological Congress 1910, held in Stockholm, Baron G. DE GEER formulated his widely accepted doctrine that the Scandinavian uplift occurred in *Tertiary* time and affected large sections of peri-Scandic lands including as well Greenland and Spitsbergen. In accordance with E. SUESS[225]),

[224]) H. REUSCH (1901, p. 241) explained his concept of "*palaeic surfaces*" as follows: 'In countries where the contrast between the old and new forms of the landscape is well pronounced, it may be convenient to have a word for the original relief as opposed to the later forms of denudation. As an expression of this kind I have used in my paper the words "*palaeic surface*" for the old surface. With regard to Norway I am inclined to define it more closely as that surface which existed, with its pertinent forms, before the quaternary period, consequently the tertiary surface. But as the exact date of the new cycle of erosion cannot yet be fixed, one hesitates in using such a definite expression as prequaternary or the like.'

[225]) EDUARD SUESS gave a flowery expression of his thoughts on the age of oceanic depths in the North Atlantic: '... undertake an excursion with us; we would go to Scotland. An isthmus, some 1,200 feet high at the narrowest part—Sir Wyville Thomsom's ridge—would lead us first to some isolated peaks, nearly 3,000 feet high, and over a rising country to the high peaks of the Faröes. We would observe land-born coal-beds between the great coulées of basalt. Proceeding further, we would

he thought that the North Atlantic was formed then by the subsidence of a land area coexistent with the Scandic. In his chain of evidence the emplacement of the Brito-Arctic basalt province was the causal link with the deep-seated epeirogenic process. He considered Iceland and the Faeroes as remnants of this drowned land mass which had been widely covered with volcanics before it disappeared. In addition to evidence derived from the basalt province, the Tertiary age of such vertical displacements affecting the Scandic region was deduced from the Cenozoic stratigraphy of Spitsbergen (DE GEER, 1919). In a paper of 1913, J. J. SEDERHOLM disclosed the existence of fairly recent fissures and fractures (*'Bruchspalten'*) which are particularly frequent in the south-western sections of Fennoscandia (*i. e.* Baltic Shield including the Caledonides). He suggested that the whole western flank of this physiographic block had been elevated[226]) along *step fault systems*, including conjectural faults running along the continental slope off Norway's coast. This was indeed confirmed through subsequent submarine investigations mainly carried out by O. HOLTEDAHL and his son[227]). Conspicuous longitudinal depressions dividing the shelf into inner and outer

travel to the north-west, over a broad tract of rocky land some 1,200 or 1,300 feet high; then first meet an isolated mountain of about 1,800 feet, and from there ascend to the volcanic mass of Iceland, where we should see those vast fields of lava, dotted with active volcanoes, and observe the long faults and open rents cutting through the masses of lava and trending across Iceland in a broad arch, first from south-west to north-east, then northward, beyond the volcano Askja to Husavik; and beyond this broken and breaking zone we might gain the great "effondrement" or "Kesselbruch" of Faxafjord, beset all round by volcanoes and hot springs, from Snaefells Jökull to Reykjavik. In following the rents so well described by our indefatigable THORODDSEN, we might detect faulted plant-bearing beds, and recognise the equivalents of the Faröe coal-seams. If some younger and more impressible student be in our company he might well exclaim, in face of these plant-bearing beds, stretching on to Greenland and showing the existence of a vast dry land in late times, and in face of these rents and volcanoes: "Verily, Professor, the sagging-down of the North Atlantic is the most recent event; it is going on before our eyes; and as the highest mountain chains are the youngest, so also are the deepest parts of the planet the most recent." I fear I should not know how else to answer the student than, "Really, I do not know." (E. SUESS, 1893, p. 183).

[226]) G. DE GEER (1912, 1919, 1926) and J. J. SEDERHOLM (1913) emphasized the *remarkably oblique and asymmetrical rise of Scandinavia* and the corresponding depression of the Baltic. Furthermore, they made a clear distinction between the pattern of Tertiary displacements and that of "crustal recovery" following the waning of the continental Pleistocene ice. The latter movement is entirely different and focused around the Gulf of Bothnia, where a present uplift of 1 cm per year is recorded. In a treatise on the geomorphology of Finland, V. TANNER (1938) discusses some general problems related to Fennoscandia's lopsided character. The subject of this "oblique uplift", seen in a wide scope of Balto-Laurentian similarities, has more recently been reviewed by O. HOLTEDAHL (1953).

[227]) O. HOLTEDAHL (1940, 1950); H. HOLTEDAHL (1956).

parts were located and found to be of fault origin. Norway's shelf[228]) may thus be regarded, says H. HOLTEDAHL (1956, p. 52), 'as a "palaeic" surface of Tertiary age, subjected to block-faulting and to denudation by marine and subaerial agencies during changing sea-levels'. He further discussed the *evidence of lower relative sea-levels* based on studies of the Norwegian shelf, as well as comparisons with shelf sections off Scotland, Ireland, the Faeroes and Iceland. 'One must consider' he concluded, '*the* 270 *m level as a possible former marine base level* present over a considerable area'. Yet, he found it difficult 'to adjudge whether this presumed sea-level dates from pre-glacial or from Pleistocene times' (*op. cit.*, p. 56). He added that this lowering of the sea-level would exceed the amount of postulated *eustatic changes*[229]) due to the storage of ice during the maximum glaciation. (According to P. WOLDSTEDT, 1961, p. 244, this is now suggested to be of 100–120 meters).

In the last decades great efforts have been made to investigate the most recent modifications of the landscape resulting from changes of climate, vegetation, glaciers, and sea-level. In northern lands, in particular, post-glacial displacements of shorelines are ubiquitous; they are mostly of negative character[230]) and therefore preferably explained in terms of "crustal recovery". Characteristics of the *isostatic readjustment* derived from radiocarbon-datings[231]) yield uniform patterns of strongly decreasing rates of uplift from the time of the deglaciation to the present. As to Greenland, indeed, 'at many places one discovers the greatly elevated coast line' admitted C. GABEL-JØRGENSEN and J. EGEDAL (1940), but added that 'at other places the ruins of Eskimo houses lie awash on the beach and clearly proclaim the sinking of the land' (*op. cit.*, p. 8). The latter situation refers mainly to locations in southern Greenland[232]).

In view of the sparcity of reliable data on relative sea-

[228]) Characterized as "fissure type" shelf by A. GUILCHER (1958, p. 219).

[229]) Intrigued by Prof. LOUIS AGASSIZ's postulate of widespread continental glaciation in the northern hemisphere, C. MACLARAN (1842) introduced the *concept of glacio-eustasy*: '... we find that the abstraction of the water necessary to form the said coat of ice (on the northern hemisphere), would depress the ocean about 800 feet. Admitting further, that one-eighth of the fluid yet remains locked up in the existing polar ices, it follows that the dissolution of the portion which has disappeared would raise the ocean nearly 700 feet. The only very uncertain element here is the depth of the ice, but even if this should be reduced one-half, we would still have an agent capable of producing a change of 350 feet on the level of the sea' (*op.cit.*, p. 365).

[230]) *Negative strandline changes* are the result of a relative rise of the land or a relative lowering of the sea-level.

[231]) W. R. FARRAND (1962); L. WASHBURN and M. STUIVER (1962).

[232]) *Cf.* R. BØGVAD (1940), J. EGEDAL (1947), E.W. NIELSEN (1952).

level changes[233]), any thoughts on possible former land configurations[234]) in the realm of the Faeroe-Iceland-Greenland Ridge remain speculative. It is no wonder that the literature is full of controversies whether this threshold at times effectively bridged Europe with America. Admittedly, not many geologists worried seriously about this problem, although since PLATO's time the myth of the drowned "Atlantis" stirred man's phantasy. The problem remained transcendental; to the geologist the answer was as illusory as was a glance on the moon's dark side at that time. Yet, there was an answer, although drastic, that is the bold concept of the splitting "Pangaea", propelled and popularized by A. WEGENER, professor of meteorology and geophysics. His theory[235]) left little of the stratigraphic time column to the history of the North Atlantic. With this he made the problem an issue among biogeographers, paleomammalogists, paleoclimatologists, and geophysicists, excluding historical geology. It is true that the drift concept greatly stimulated paleogeographical investigations. But the theory also overshadowed the unbiased research; too often it challenged a direct response that was "*pro*" or "*contra* WEGENER" rather than straight to the point. Hence, questions of the existence of former land connections in the North Atlantic led to lively disputes particularly among the biological sciences. Indeed, there are problems of great significance to paleontology, biology and paleoclimatology hinging on the structural and physiographical evolution on the Faeroe-Iceland-Greenland Ridge. The biological aspect is the history of the distribution and dispersal of animals and plants. The climatological aspect involves the rôle of the Gulf Stream in relation to Pleistocene Glaciation.

Biogeographical implications. The early explorers of North America were surprised by the similarity between the animals encountered there with those known to them in the Old World; others were quite different and characteristic of the New World. Therefore, since the 18th century zoologists had postulated that there existed a former connection between the two continents. By the end of the last century it became clear that

[233]) Most geologists agree to changes of sea-level, independent of land movements (*i.e.*, tectono-eustasy), in the form of glacio-eustacy (*cf.* p. 222). 'But non-climatically controlled oscillations of sea level', says R.W. FAIRBRIDGE (1961, p. 173), 'are often excluded from the working philosophy of geologists, although such movements have been considered as most probable by leading theoreticans'. From Pleistocene eustatic curves, FAIRBRIDGE (*l.c.*) reached the conclusion 'that there are overriding controls of eustasy that supersede both climatic and local tectonic influences.'

[234]) J.W. GREGORY (1929, p. lxxiv) suggested the name "*Icelandic Transatlantic Land*".

[235]) Compare pp. 167–70.

faunal resemblances between different continents are controlled by the existence of practicable *migration routes*, changing through geologic time. It was noted as well that the Arctic floras on both sides of the North Atlantic are very similar but this resemblance does not extend to more temperate floras. Many Arctic and Sub-Arctic species are confined to the North Atlantic regions while others have large gaps in their distribution in Siberia and western North America. Such species are said to have an '*Amphi-Atlantic*'[236]) distribution pattern (E. HULTÉN, 1958; E. DAHL, 1958). From Scandinavia to Scotland, the Faeroes, Iceland, Greenland, and into Canada, there seems to be gradual transition from a predominantly European flora in the east to a predominantly American flora in the west. There are also close phytogeographic connections between Spitsbergen and Northeast Greenland. This suggests that migrations across the North Atlantic have taken place, either by long-distance dispersal or across a former land connection between North America and Europe. Since the latter hypothesis refers to pre- and inter-Glacial times the theory of *survival* of plants in ice-free refugia is implied as well. Whatever the history of the *North Atlantic biota*[237]) may be, there is a distinct European character in the flora and fauna of Iceland. According to E. DAHL (1963) in the Iceland flora Amphi-Atlantic and European elements adapted to long-distance dispersal are under-represented. As he says, 'there is no evidence that the Amphi-Atlantic and European species reached Iceland by long-distance dispersal, whereas there is evidence that this was the case by the immigration of the North America element' (*op. cit.*, pp. 179–81). With regard to Greenland[238]), C. H. LINDROTH (1960) likewise reached the amazing conclusion that 'Greenland and Iceland once had a firmer connection with Europe but nothing indicates a direct land-connection between Greenland and North America proper. Davis Strait has certainly for a long time functioned as a barrier, to the flora as well as to the fauna' (*op. cit.*, p. 135). Thus, the idea of an earlier land connection between Europe and North

[236]) The term "*Amphi-Atlantic*" (German: amphiatlantisch) was proposed by F. ØKLAND (1927, p. 352) in order to designate animal (and, of course, also plant) *species common to Europe and North America* but absent from Asia and thus believed to indicate direct faunal interchange across the North Atlantic. (The term would be equally suitable for species common to Africa and Central or South America, if any, but is used for the northern continents only).

[237]) A. and D. LÖVE, *Editors*, (1963). North Atlantic Biota and Their History. A symposium held at the University of Iceland, Reykjavik, July 1962, under the auspices of the University of Iceland and the Museum of Natural History. Pp. 1–430, ill., Pergamon Press (Oxford).

[238]) The question as to what extent the Norse colonists in Iceland and Greenland had an impact on the flora of these islands has been discussed by many authors; a summary statement was given by E. DAHL (1963, p. 174).

America occurred in particular to biogeographers who wished to explain these striking similarities of both sides of the North Atlantic. However some of the reasoning on this problem has been a *circulus vitiosus*; biologists proposed geological possibilities, which geologists tended to accept as conclusions and *vice versa*. But bitter controversies arose as well. In response to a postulate made by botanists, T. THORODDSEN, as early as 1904, clearly denied the existence of a North Atlantic land-bridge in post-Glacial times[239]). Yet the advocates of a very recent land-bridge declared him an 'unbeliever' who uses his scepticism as fact[240]). Zoogeographers struggled within their own ranks when they criticized R. F. SCHARFF's suggestion that the reindeer had utilized an 'Americo-European land-connection' (one over Scandinavia and Spitsbergen to Greenland, in particular[241])). In his next paper[242]), this ardent supporter of the North Atlantic land-bridge parried by quoting F. NANSEN's new conclusions concerning a late Cenozoic lowering of the sea-level of 500 m[243]). SCHARFF had to modify his original concept, however, and now favored the Scoto-Icelandic-Greenlandic route. To T. ARLDT (1919) this seemed so convincing that he classified this North Atlantic land-bridge as 'eine der am sichersten feststehenden palaeogeographischen Tatsachen' (*op. cit.*, p. 83).

In 1910, shortly before A. WEGENER propagated the drift hypothesis, H. F. OSBORN published his fundamental compilation on the age of

[239]) T. THORODDSEN (1904, p. 399) says, '... at de geologiske Iagttagelser ikke støtte Hypotesen om en postglacial Landbro, tværtimod, fra geologisk Synspunkt maa Hypotesen betegnes som fuldstændig uholdbar.'

[240]) H. G. SIMMONS (1905, p. 155) argues, '... THORODDSENS bevisföring ... blott visa, att han icke tror på existensen af en sådan landförbindelse, och denna sin tro vill han uppställa som norm för dem, ...'.

[241]) R. F. SCHARFF (1899, pp. 155–60).

[242]) R. F. SCHARFF (1909).

[243]) F. NANSEN (1904, p. 173) says, 'It seems highly probable that the Færoes and Iceland were once connected by a basaltic plateau emerging above sea-level. Although the plateau between the islands may have been depressed by dislocations and tectonic movements, its present relatively level submarine surface—which seems to mark an ancient sea-level—cannot have been formed in this way. Its great distance from any land makes it also impossible that it has been much levelled by deposition of terrigenous waste of any kind. We are thus, according to my view, obliged to assume that the ancient plateau or ridge has been abraded towards a mean base-level of erosion during some previous period when the shore-line, perhaps with several oscillations, stood on the average about 500 m lower than now. The basalts and possibly other volcanic rocks, building up the upper part of the ancient plateau, were easily cut back by the conjoint action of subaerial erosion and marine denudation. If the Wyville Thomson Ridge, the Iceland-Greenland ridge, and perhaps also the ridge between Greenland and Baffin Land, are built up by solid rocks, we are obliged to assume that they have been abraded towards a mean base-level of erosion just as we have seen above, and during the same period.'

mammals on the northern continents. This set the first firm base for the discussion of the problem, since the spreading of land mammals obviously depends on land connections, including sea ice. Thus in following decades G. G. SIMPSON carefully analyzed the intercontinental relationship of the **Holarctic mammals** and the probable dates of Cenozoic migrations[244]). He found that the *Bering 'bridge'* was the main or only route of intermigration. In modern textbooks his conclusion has been generally adopted. It should be mentioned, however, that SIMPSON himself considered the possibility of a *North Atlantic 'bridge'* as well[245]). Yet, the only period that appeared to be reasonable from the viewpoint of paleomammalogy is the Lower Eocene. SIMPSON's inference, in turn, has since been confirmed by B. KURTÉN (1966) on the basis of later studies of early Tertiary mammals in Asia. From those it became evident that 'intermigration between Europe and North America, by a direct route not crossing Asia, was marked in the late Paleocene and very intense in the earliest Eocene, but then ceased' (*op. cit.*, p. 4). According to my conclusions reached on previous pages, this exclusive period of intermigration across the North Atlantic—suggested by paleomammalogsits—is the time when the Brito-Arctic basalt eruptions initiated and their field was the site of an (?intercontinental) rise.

Secular climatic changes have been recorded throughout geologic time[246]). They were of particular importance to the evolution and distribution of the land vertebrates whose migration radiated from Holarctic centers of dispersal[247]). Foreshadowed by a gradual cooling[248]) during the Tertiary period, the Pleistocene glaciation of the northern continents is considered as one of the most amazing climatic events in the earth's history. Peculiar to this event are the repeated, relatively

[244]) G. G. SIMPSON (1947) concluded that the major *faunal interchanges* between Eurasia and North America 'occurred in early Eocene, late Eocene, early Oligocene, late Miocene, middle to late Pliocene and Pleistocene. There was little or no interchange in the middle Eocene and middle to late Oligocene. Each interchange involved migration in both directions, but there was probably more movements from Eurasia to North America than in the opposite direction. All interchanges were selective, and they became increasingly limited from Eocene to Pleistocene. The most important selective influence was probably the relatively cold climate of land connection. This connection was probably from Siberia to Alaska throughout the Cenozoic and was in almost continuous existence with important interruptions in parts of the Eocene and Oligocene and perhaps shorter interruptions at later times' (*op. cit.*, p. 614).

[245]) G. G. SIMPSON (1940, p. 149; 1947, p. 658).

[246]) C. E. P. BROOKS (1949).

[247]) W. D. MATTHEW (1915, 1939).

[248]) R. F. FLINT (1957, p. 488).

short successions of glacial and interglacial epochs. In order to explain such irregularity sophistic calculation were made again and again; some involve planetary dynamics and solar fluctuations, others emphasize the variabilities of physical geography[249]) or consider the combined effects (*e.g.* R. F. FLINT's *'solar-topographic concept'*). Most of the 'terrestrial' reasoning on glaciation goes all the way back to Sir CHARLES LYELL's classic "Principles"[250]), first published in 1830. The dependence of climate upon the distribution of the sea and the relief of the land was then established. Later, J. D. DANA in his "Manual of Geology" called attention to the prevalence of fjords in all glaciated regions. He considered these valleys as carved by pre-glacial streams thus indicating that *the land was remarkably elevated prior to the glaciation*[251]). G. F. WRIGHT and W. UPHAM (1896, p. 331) elaborated further on DANA's view by assuming that this uplift occurred in the *Pliocene* and resulted in a belt of continuous northern lands prior to the "Ice Age". They postulated thus late Tertiary connections 'from North America across the area of the shallow Behring Sea and Strait to northern Asia, and from Norway across the now submarine plateau . . . to the Färöe Islands, Ireland, and Greenland' (*l. c.*). This conclusion had been reached independently thirty years earlier by R. A. C. GODWIN-AUSTEN through studies of the 'Crag' formation in northwestern Europe. The Pliocene land stretching across the Scandic was even shown on a paleogeographic map. GODWIN-AUSTEN did not fail to mention that 'the greater extent of circumpolar land would exercise a great influence on the course of the North Atlantic Ocean-current' (*op. cit.* p. 241), although he had in mind a diverted warm current following the south shore of his hypothetic land rather than any implication of polar glaciation. Such consequences, however, were soon considered in further discussions on the validity of DANA's concept. It was namely A. R. WALLACE (1880) who came to evaluate the effects of an emerged Scoto-Greenlandic land barrier upon the flow of the ocean currents. He visualized that 'the whole of the warm waters of the Atlantic with the **Gulf Stream**, would then be shut out from Northern Europe, and the result would almost certainly be that snow would accumulate on the high mountains of Scandinavia till they became

[249]) W. SARTORIUS v. WALTERSHAUSEN (1865, pp. 369–70) concluded, 'So bleibt uns denn nur noch die einzige Hypothese übrig, welche zur Erklärung aller in der Diluvialzeit vorkommenden Glacialerscheinungen unter allen Umständen ausreicht, nämlich eine veränderte Reliefform der Erde mit Einschluss gewisser Wassercomplexe anzunehmen.'

[250]) C. LYELL (1830, pp. 104–24).

[251]) J. D. DANA (1863, p. 544) assumed that 'an elevation of the continent in its northern regions of a few thousand feet is sufficient to account for the existence of a *Glacial epoch* in the earth's later history; and an elevation of 5,000 feet is as probable as a subsidence of 5,000 feet.'

glaciated to as great extent as Greenland, and the cold thus produced would . . . cover the Grampians with perpetual snow, like mountains of the same height at even a lower latitude in South America' (*op. cit.*, p. 145). The North Atlantic barrier concept and its implied deflexion of the Gulf Stream must have profoundly modified the regime of air circulation as well. Such **paleometeorological** aspects have been discussed by F. W. HARMER (1901, 1925), who attempted to reconstruct the pressure distribution and storm tracks which would prevail under these conditions. Stimulated by HARMER's conclusion H. J. E. PEAKE and H. J. FLEURE (1926) aimed at a complete *explanation of the Pleistocene cycles in terms of elevation and depression of the North Atlantic barrier.* According to their theory 'the land [barrier] would have been sinking during the earlier part and rising during the latter part of each of these interglacial epochs' (*op. cit.*, p. 5). That similar thoughts were developed independently in Swedish[252]) and German[253]) papers may strengthen the idea. Yet, there was also objection, namely by W. BEHRMANN (1948). In his picture of the northern glaciation a relatively warm current is needed in the Scandic Sea in order to provide a sufficient supply of moisture. Moreover, he has some doubt as to the repeated oscillation of the submarine ridge relative to sea-level so that several times the Gulf Stream was effectively barricaded[254]). More recently the barrier concept has been applied once more by M. EWING and W. L. DONN (1956, 1958), although these authors assume physiographically stable conditions. Their "Theory of Ice Ages" is principally based on the hypothesis of pole-wandering. The Ice Age had thus initiated when the poles migrated into thermally isolated locations such as the Arctic Ocean and Antarctica. The fluctuations of glacial with interglacial climate were then mainly controlled by the extension of sea ice in the Arctic. This, in turn, is thought to have been effectively controlled by glacio-eustatic sea level changes (of about 50 fathoms) steering the interchange of cold and warm waters at the Faeroe-Iceland-Greenland Ridge.

[252]) H.W. AHLMANN and B. HELLAND-HANSEN (1918).

[253]) F. KERNER v. MARILAUN (1941); J. BLÜTHGEN (1941, 1942); W. WUNDT (1944).

[254]) W. BEHRMANN (1948) explained, 'mir scheint nämlich gerade, wenn man eine sperrende Islandschwelle zwischen den Meeren annehmen wollte, das Gegenteil von dem erreicht zu werden, was man erklären will. Unwahrscheinlich ist schon, dass sich entsprechend der Vierzahl der Vereisungen viermal die Islandschwelle um den immerhin sehr hohen Betrag von 500–600 m gehoben haben soll, um während der Warmzeiten wieder hinunterzutauchen. Nur wenn auch während der Eiszeiten im Skandik ein relativ warmer Golfstrom vorhanden ist, kann die Erscheinung der Eiszeit befriedigend gedeutet werden. Damit die Gletscher wachsen, ist nicht nur die Kälte, sondern vor allem Feuchtigkeit notwendig. Schnee, und damit Gletscher, gibt es nur im ozeanischen Klima in ausreichendem Masse.'

There are thus many questions of foremost importance; their answers may be found when more is known about the history of the North Atlantic, in particular the geologic evolution of the Faeroe-Iceland-Greenland Ridge.

B. The Tertiary of East Greenland

As to Tertiary formations encountered in East Greenland, on the Tectonic Map three major rock groups have been distinguished:

- *sedimentary successions*, transgressing across pre-basalt rock units of different ages,
- *basaltic lava flows* and *minor intrusions*,
- acid and basic *plutonic rocks*, mainly of alkaline type.

Structural features reflecting Cenozoic disturbances have been recorded in both Central and Northeast Greenland. The shallow folds and local thrusts observed in Central East Greenland between 71°30′ and 72°40′ N are apparently of 'post-basalt' age. Those traceable in Northeast Greenland, north of 80° N, cannot be dated accurately; yet they are likely to have affected the marine succession at Nakkehoved (northern tip of Kronprins Christian Land) which is of Cretaceous or Tertiary age.

Sedimentation

Terrestrial formations transgressing across a late Mesozoic to early Cenozoic land surface have been found in various places in the coastal region between 74° and 75° N. They are of insignificant thickness. Fluviolacustrine sandstones prevail, but deltaic formations with coarse clastics have been encountered as well, *e.g.*, a fan of debris poured from western sources across Wollaston Forland[255]). The deposition of these formations preceded the major eruption of lava flows. Sandstones and shales, similarly constituting sub-basaltic sequences, are known from Sabine Ø and western Clavering Ø. At the latter place, however, basaltic debris was found as rock components thus indicating surface volcanism in a (?western) source area. Plant fossils are frequent; yet collections have been available from only Sabine Ø. They have been described first by O. Heer (1874) as 'Miocene', but later, F. J. Mathiesen (1932)—on the basis of the "Danmark"-Expedition collections—referred to them as of *Paleocene* or *earliest Eocene age.*

Interbasaltic terrestrial beds, however, are widespread, although all of them are very thin. They accumulated at the disintegrated and bevel-

[255]) A. Vischer (1943, pp. 161–62).

led surfaces of lava floods. These beds include agglomeratic material as well as products of decomposed volcanics that were subsequently redeposited. Yet in the lowermost sections of the basalt plateau of inner Scoresby Sund, for example, E. WENK (1961b, p. 43) found that in addition to volcanic material (zonal, highly twinned plagioclase, pyroxene, glass, and in places olivine) the intercalated beds often contain numerous minerals of metamorphic origin (quartz, faintly inversely zonal oligoclase, biotite, and garnet). He thus concluded that the latter components were 'derived from the mountain ridges and outliers of Caledonian crystalline rocks which during the first stage of flooding still rose above the basalt sea. Together with the organic remains they show that erosion and sedimentation processes were going on between they various phases of effusion, and that these phenomena were repeated rhytmically.' (*l.c.*). The composition and type of sediment may greatly vary from one intercalated bed to the other. There are disintegrating coaly beds as well as agate beds with silicified tree-trunks. Frequently the beds consist exclusively of red bole. Those are predominant among the intercalations in the upper part of the Scoresby Sund plateau. In contrast, in the northern plateau region, extending from Kejser Franz Josephs Fjord to Shannon Ø, exposures of interbasaltic beds are rare. However, a significant feature—a *fossil river bed*—was discovered by A. K. ORVIN (1931) north of Mackenzie Bugt (Hold with Hope). The river bed is carved in and overlain by basalts; it consists of 15–20 m of dark brown conglomerate[256]) including a great many of silicified chunks of wood[257]). Pieces of coal have been found as well.

Marine Tertiary strata have been found below and above the plateau basalt formation and as interbasaltic beds as well. From the southern edge of the East Greenland eruptive field, *i.e.* at 68°30′ N, the "*Kangerdlugssuaq Sedimentary Series*" has been mentioned (see pp. 164). This sub-basaltic succession is some 200 m thick and consists of terrigenous beds which include marine fossils of Senonian age but grade upwards into beds with fossil plants of presumably 'early Eocene age'. Another occurrence of sub-basaltic strata was found by W. MAYNC[258]) at the northeastern tip of Lille Pendulum Ø, *i.e.* at 74°40′ N. The "*Lille Pen-*

[256]) According to A. K. ORVIN, 'the pebbles and cobbles consisted of more or less rounded stones of dark siltstone, and the matrix was made up of sand, and was partly calcareous' (*op.cit.*, p. 470).

[257]) A. K. ORVIN (*op.cit.*, p. 471) presents the photograph of a silicified trunk, some 0.5 m thick, of *Piceoxylon laricinoides* x. sp. He felt quite certain 'that the wood found in the conglomerate has grown on Greenland in the intervolcanic period represented by the fossil valley, and the growing site cannot have been situated very far from the spot where the wood is now found.' (*Op.cit.*, p. 473).

[258]) A. VISCHER (1943, p. 129); W. MAYNC (1949, p. 40).

dulum beds" include both plant remains and marine fossils; the conglomeratic nature of part of the strata indicates a nearshore formation. There, again, among the rock components basaltic debris has been found, although the deposition of the bed predates all of the local lava eruptions. From Hochstetters Forland, south of Kap Oswald Heer, beds including fossil plants[259]) as well as marine mollusks[260]) have been reported. It is unknown whether they correspond to those exposed at Lille Pendulum Ø.

Post-basalt marine successions transgressing across the lava field south of Scoresby Sund are known as "*Kap Dalton Series*" (Eocene[261])) and "*Kap Brewster Series*" (Miocene[262])), see pp. 194, 195. The faunal assemblages found in these marine series bear closer relationships to the Old World faunas than to those known from corresponding North American provinces[262]).

Surface volcanism and minor intrusion

In Fig. 77 it was shown that East Greenland's Tertiary basalts are regionally grouped into four distinct fields. Their varied development was apparently controlled by the structure of the pre-basaltic crustal blocks. Where denuded basement complexes (either Caledonian or Precambrian) formed the early Tertiary land surface or where such complexes were covered only by thin blankets of sediments, the invading basaltic magma reached the surface through narrow feeding channels and hence emplaced in the form of lava floods. This was essentially the case in the huge basalt plateau south of Scoresby Sund (cf. Pl. I). It is also true for the lava sheets that occur in the ice area north of Hobbs Land (74° N). In the coastal area north of Kajser Franz Josephs Fjord,

[259]) O. Heer (1874).

[260]) T. Fuchs (1883) re-examined the rock samples brought back by the "Zweite Deutsche Nordpolarfahrt". He discovered impressions of marine shells ('Conchylien') and described them as follows: '... finde ich übrigens auf den mir von Hochstetters-Vorland vorliegenden Stücken noch zahlreiche Abdrücke einer kleinen rundlich-dreieckigen Muschel, welche ganz einer *Astarte* gleichen, sowie den Abdruck eines grossen glatten Pecten, ähnlich dem *P. magellanicus* Gmelin von Neufundland.' (*Op.cit.*, p. 5).

[261]) J. P. J. Ravn (1909, 1933) concluded an Early to Middle Eocene age on the basis of the fauna; K. L. Henriksen (1917) confirmed a Middle Eocene age as to the fossil insects encountered; F. J. Mathiesen (1932) determined the fossil flora as of Paleocene to Eocene age. T. Sorgenfrei (1940) guessed a Middle Oligocene to Lower Miocene age on the basis of the crustacea genus *Coeloma*, yet the evidende on this is weak and has not been strengthened since.

[262]) Y. M. Hassan (1953).



Fig. 78. Plateau of Tertiary flood basalts covering the northeastern tip of Wollaston Forland. In the very foreground Caledonian crystalline rocks emerge at Falkebjerg (which is part of the "Hühnerbjerg block", compare Fig. 70). The basalt sheets in the center overlie Lower Cretaceous beds. In the left middle ground is Albrechts Bugt. The mountains in the background are part of Kuhn Ø. — Air-phot. F. SCHWARZENBACH, 1956.

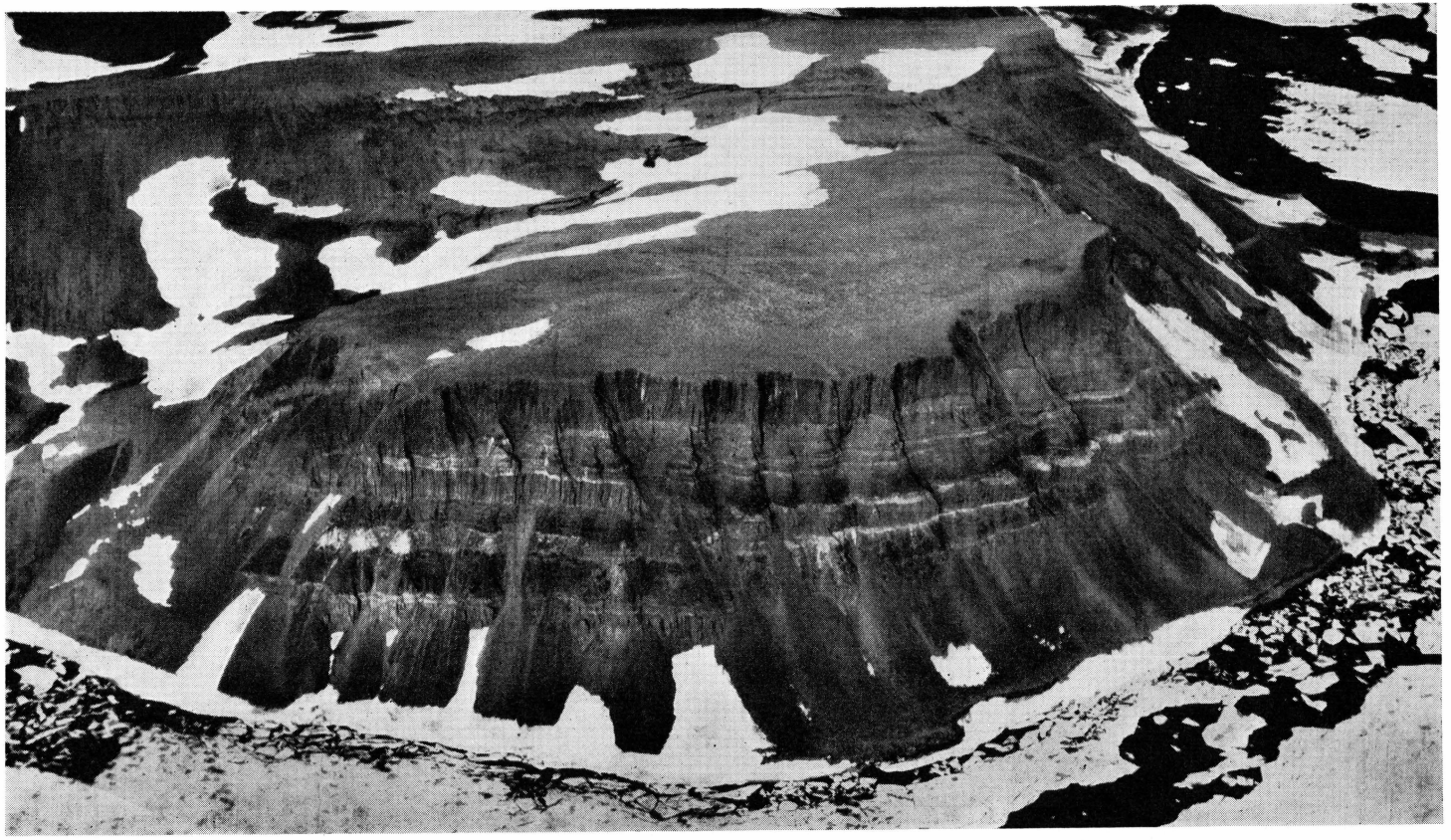


Fig. 79. Tertiary dolerite sills intrusive into Cretaceous strata at the north shore of Æbeltoft Vig, Traill Ø. Note the up-stepping featured by the middle and upper sills. – Air-phot. W. DIEHL, 1957.

although some dolerite sills settled into the relatively thin Mesozoic cover, the magma found its way through emerging to the surface (Fig. 78). In these northern two plateau regions the total thickness of flood basalts presumably did not exceed the order of 1,000 meters[263]). For the southern plateau, however, L. R. WAGER (1947, p. 45) arrived at a thickness 'of certainly 6.5 km and probably a good deal more'. The remaining regional field, where minor intrusions are ubiquitous, stretches along the coastal area from Scoresby Sund to Kejser Franz Josephs Fjord. This field, bounded towards the west by the "post-Devonian major fault", includes a pile of several thousand meters of Upper Paleozoic but mainly Mesozoic strata resting on the Caledonian trunk. Between Kong Oscars and Kejser Franz Josephs Fjord, moreover, this pile of flat-lying sediments is underlain by broadly folded Old Red Sandstone, several thousand meters thick. No author has felt competent to estimate the entire thickness of these late and post-Caledonian cover rocks. The only attempt to visualize the situation was made by H. BÜTLER (1948, p. 85, fig. 1) who assumed in the area of eastern Traill Ø the base of the Old Red Sandstone to be at a depth of some 8 km. Even by disregarding the succession of Old Red Sandstone (which is anyhow presumably missing in most of the field south of Kong Oscars Fjord), there remains a *considerable volume of well stratified sediments which were readily disposed to host the ascending basalt magma in the form of innumerable sills and dikes* (Fig. 79). In the area concerned the pile of sediments apparently was of appropriate size and making to absorb the bulk of the invading magma so that here not much or even no basalt made its way through to the surface. The relation of dolerite intrusions to thickness of sediments revealed in this part of the Tertiary province is essentially in agreement with what S. W. CAREY (1958b) found to be a rule in other eruptive fields. With reference to this paper it is also interesting to note that in East Greenland, the only dolerite intrusions seen to form *cone sheets* occur on Clavering Ø[264]) where the sedimentary cover is relatively thin. A rather flat cone-shaped sheet related to the surface volcanics of western Clavering Ø is shown on Fig. 80.

Intrusive centers and sub-volcanic rocks

The region-wide extrusion of flood basalts was accompanied by the emplacement of plutonic bodies (cf. Fig. 77, nos. 1–9). There are two

[263]) H. BÜTLER (1959, p. 151) estimated the total thickness of the Tertiary basalt pile exposed in eastern Gauss Halvø as up to 700 m.

[264]) H. G. BACKLUND and D. MALMQVIST (1932, pp. 14–17); H. G. BACKLUND (*in* T. KROKSTRÖM, 1944, p. 65).



Fig. 80. Cone sheet related to the Tertiary surface volcanics, exposed on Hallebjergene, western Clavering Ø. — Air-phot. F. SCHWARZENBACH, 1956.

regional groups of intrusive centers; the first includes the intrusions around Kangerdlugssuaq (68° N)[265]), namely:

(1) *Kap Edvard Holm* (gabbros, ultrabasic rocks),

(2) *Kangerdlugssuaq* (quartz-syenite, syenite, nepheline-syenite),

(3) *Skærgaardshalvö* (gabbros, ferrogabbros, granophyres),

(4) *Lilloise Bjerge* (syenites, nepheline-syenites).

The second group of intrusive centers, entirely shown on Map 3, gathered along a line extending from the Werner Bjerge massif (72° N) across Kong Oscars Fjord to Kap Parry (Traill Ø, 72°25′ N). Another center occurs farther north at Kap Broer Ruys (Hold with Hope, 73°30′ N). The petrological characteristics of these centers are as follows:

(5) *Werner Bjerge massif*[266]), composite intrusion of alkali-granite, alkali-syenite and porphyries, nepheline-syenite, monzonite, syenodiorite, syenogabbro, and pyroxenite. The body of intrusive rocks is partly surrounded by volcanic breccias. Numerous basic dikes cut across the alkali massif and its country rocks; lamprophyres are of local appearance and dolerites can mainly be referred to the regional basalts. There is widespread hydrothermal decomposition of the plutonic rocks, and, related to this late to post-magmatic event, ore mineralization[267]) took place, including economic occurrences of molybdenum, lead and zinc.

(6) *Pictet Bjerge complex*[268]) consisting of four minor intrusions located between Kong Oscars Fjord and the Werner Bjerge massif: i) *Kap Syenite* (calc-alkali-syenite), ii) *Theresa Bjerg* (various types of syenite, porphyrites, gabbrodiorites, and volcanic breccias), iii) *Pictet Bjerge* (alkali-granite), iv) *Oksehorn* (syenites, porphyrites, volcanic breccias, and basalts). In the Pictet Bjerge complex, in particular, polymict intrusion breccias (explosion, tuff and vent-breccias) constitute the roof over the syenite intrusions.

(7) *Kap Simpson complex*[269]) (alkali-granite, alkali and quartz-syenites, porphyries, volcanic breccias, basalt dikes),

(8) *Kap Parry complex*[270]) (predominantly alkali-granites). Both the Kap Simpson and Kap Parry complexes reveal intense hydrothermal

[265]) L. R. WAGER (1934, 1947); L. R. WAGER and W. A. DEER (1939).
[266]) P. BEARTH (1959).
[267]) J. BONDAM (1955, H. BROWN (1955), P. BEARTH (1959).
[268]) A. NOE-NYGAARD (1934, 1940 a), H. KAPP (1960, 1961).
[269]) H. P. SCHAUB (1938, 1942).
[270]) G. W. TYRRELL (1932).

alteration including the formation of felsic rocks as well as ore mineralization.

(9) *Kap Broer Ruys*[271]) is supposed to represent the basal wreck of a Tertiary volcano rather than a sub-volcanic body. Products of this central eruption are acid lavas (rhyolites, partly altered), volcanic breccias and tuff. H. BÄCKSTRÖM (*in* A. G. NATHORST, 1901, pp. 299–300) compared this locality with features exposed on Jan Mayen and Iceland.

The alkali massifs of Scoresby Land (nos. 5–6) and Traill Ø (nos. 7–8) are thought to have been emplaced contemporaneously. The igneous bodies cut with sharp and distinctly intrusive contacts across flat-lying arenaceous sediments, ranging in age from Carboniferous to Upper Cretaceous[272]). According to H. KAPP (1961, p. 584), contact metamorphic effects are restricted to thermal baking and the transformation of argillaceous beds into biotite-hornfels, and of sandstone into quartzite. Except for the formation of volcanic breccias (explosion-breccia[273])) and partial lifting of the sedimentary roof[274]) the emplacements of these intrusive centers had a rather *atectonic* character. In spite of the absence of truly volcanic flows it can be shown that the intrusions were shallow and near the surface. The sedimentary cover has been entirely removed from the Werner Bjerge massif (Plate XXXVII) as well as from the Traill Ø centers but is preserved in the Pictet Bjerge complex.

As to the age relations of the *regional basalt invasion* and the intrusions concerned, KAPP showed that most of the dolerites adjacent to the Pictet Bjerge complex are pre-syenitic, but that other, local dike rocks in particular those of lamprophyric composition are post-syenitic. He concluded that the ascent of basic magmas started before the intrusion of the gabbrodiorites and syenites. They, in turn, outlasted the emplacement of the post-syenitic alkali-granite.

The group of intrusive centers north of the 72nd parallel displays a striking northeast-southwest alignment, although this cannot be assigned to any Mesozoic or Cenozoic structure pattern. The only environment common to all intrusions concerned is the area of down faulted blocks into which they settled. Apart from a few basic and acid dike systems

[271]) A. G. NATHORST (1901); D. MALMQVIST (*in* L. KOCH, 1950, p. 367).

[272]) The youngest beds found close to the Traill Ø intrusive centers are of *Upper Campanian* (Senonian) age.

[273]) The term '*explosion-breccia*' as defined by G. W. TYRRELL (1928) refers to the shattering of the sedimentary cover and to auto-brecciation of the invading igneous rock that caused the explosion action. (For further classification see H. KAPP, 1960, pp. 103–27).

[274]) See example described by H. KAPP (1960, pp. 92–94).

they did not extend into the western highground made up of Caledonian crystalline rocks. Yet, in the scope of regional geology, it is suggested that the northeast-southwest alignment of the centers might have been controlled by the structure of the buried Caledonian basement block. On previous pages attention was called to the remarkably linear arrangements of late-Caledonian granite batholiths. The Staunings Alper—Renland intrusions make up one of those 'lineaments'. It is probably more than incidental that a row of Tertiary, mainly acid, intrusions is found to continue this trend east of the 'post-Devonian main fault', which sharply cuts off the line of Caledonian plutons. There is, however, no way yet to prove or disprove such a relationship since nothing is known about the basement structure beneath the pile of Upper Paleozoic to Mesozoic sediments. Among the authors referred to above there is not doubt that the intrusive centers around *Kong Oscars Fjord are syngenetic products of a truly magmatic invasion, including magmatic differentiation* (gabbrodiorite → syenite → alkali-granite). Moreover, the eumagmatic nature of these intrusions is favored by the associated ore mineralization. It is thus safe to assume that the bulk of the Tertiary intrusive material was derived from a subcrustal abyss rather than from palingenetic resorts as most of the late-Caledonian intrusions did. Should there exist a relation between buried Caledonian plutons and Tertiary intrusive centers, I guess, it might be a structural one—a kind of "*telescoped*" *intrusive tectonics*—rather than a remobilization of former plutonic rock material.

Cenozoic tectonics in Central East Greenland

It has previously been emphasized that due to *early Tertiary uplift* and truncation the Mesozoic fault-block tectonics were exhumed. This refers in particular to the coastal region south of the 75th parallel, whereas in Northeast Greenland similar structures largely remained buried beneath a wide belt of coastal plain deposits. Yet the exploration of the Mesozoic and Cenozoic structural history of this region is still incomplete. It is therefore also a matter of speculation how uniform and extensive the early Tertiary peneplanation was. Formations such as the *sub-basaltic* fan of Tertiary clastics on Wollaston Forland indicate a sloping of the early Tertiary land surface towards the east. This was also found to be true for the pre-basaltic land surface in the Scoresby Sund area (cf. Fig. 76). Moreover, from the presence of *interbasaltic* coarse clastic beds—such as the fossil river bed mentioned from Hold with Hope—it is evident that during the long period of surface volcanism differential vertical displacement occurred. Although there is some indication that faults and flexures came into existence at that time no

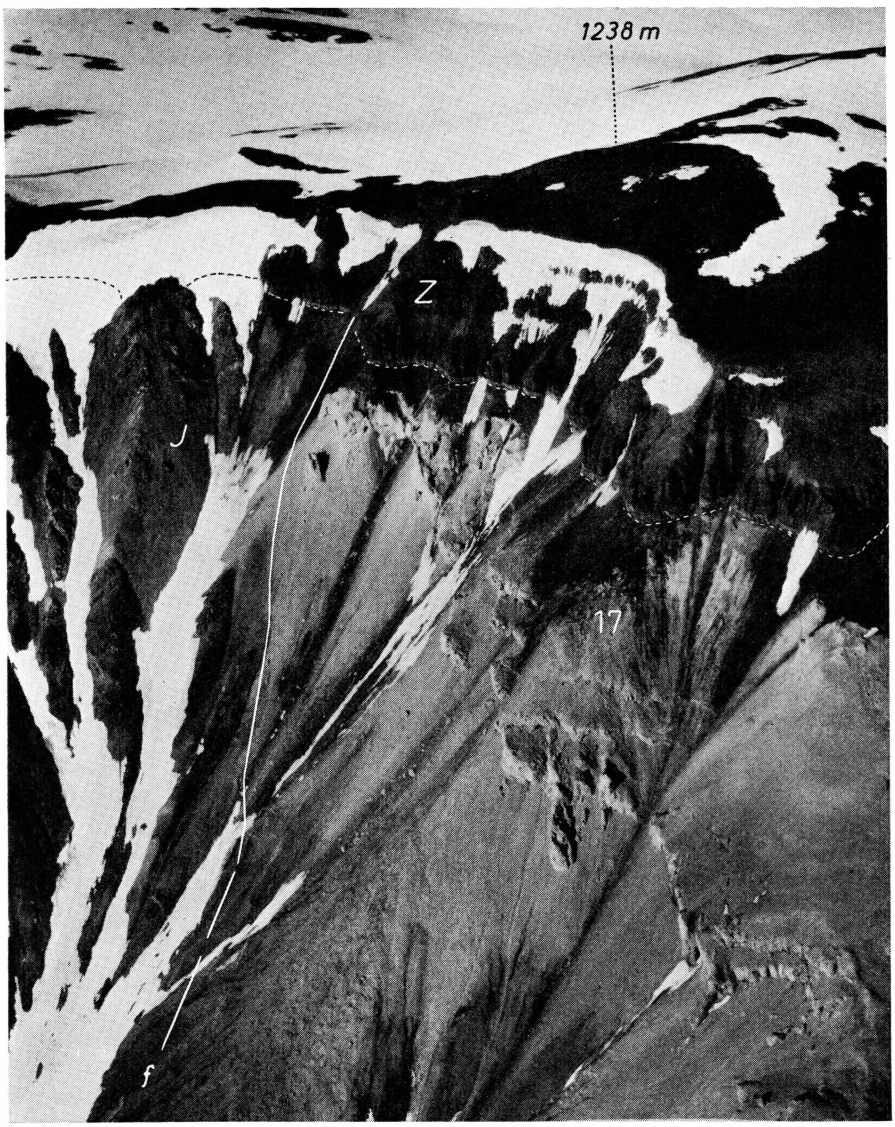


Fig. 81. Pre-basaltic normal fault (*f*) exposed in northeastern Clavering Ø. The fault displaces Upper Permian dolomite (*17*) against Caledonian mica-schists and gneisses (*J*); it was completely planed down before the Tertiary basalt lavas (*Z*) flooded the area. Note the conspicuous columnar structures at the base of the basalt sheet. — Air-phot. F. SCHWARZENBACH, 1956.

angular unconformities have yet been observed within the pile of lavas, in either the northern or southern plateaus. As to the grouping of tectonic events in relation to the emplacement of surface volcanics we are essentially limited to either pre- or post-basaltic structures. Fig. 81 is an ex-

ample of a pre-basaltic normal fault completely bevelled and then covered by a sheet of flood basalt. Another fault system shown on Fig. 82 affected the plateau basalts as well as their pavement. However, the displacement and tilting involved is best revealed by following up the varied positions of the sub-basaltic land surface (Plate XXXVIII).

In the region dominated by *minor intrusions* such as Geographical Society Ø and Traill Ø many of the fault systems can be shown to have been active during the period of basalt eruption. Late and post-basaltic throws of up to 500 m have been reported thus from Maanedal[275]), on Traill Ø. Although the intrusive centers do not show much evidence of active pushing-aside of the wall rocks, some block fault movements of local extent have to be considered as contemporaneous with the rise of the syenitic magmas. This refers in particular to the "*Vælddal fault*"[276]) adjacent to the Kap Simpson complex. This high-angle fault produced a conspicuous down-throw of the western side, *i.e.*, opposite the igneous body. At this fault, a displacement of some 1,000 m was attained in the vicinity of the pluton but it decreases rapidly farther north. The "Vælddal fault" displaces several dolerite sills, but one sill cuts also across the fault. Another fault displacing a dolerite sill for some 350 m is the *high-angle thrust* exposed in the southern section of Kongeborgen (Traill Ø). This compressional structure may or may not have been connected with the movements that caused the displacement in Vælddal. The north-northwesterly thrust block (Plate XXXIX) is of local extent (some 5 km wide only) and is cut off in the south by the transverse major fault that separates the Devonian from the Carboniferous molasse. The latter fault—a diagonal element in the pattern of the "post-Devonian main fault"—reveals a throw of up to 3,000 m, part of which was clearly attained during the Tertiary. At the opposite side of Kong Oscars Fjord, a fault of similar strike can be traced along Segelsällskapets Fjord[277]), yet there is a remarkable down-throw towards the north.

An outline of the distribution of major faults which were active in Mesozoic and Tertiary times is given on Fig. 83. The northerly running fault pattern as a whole, including transverse flexures and minor faults, show a step-like arrangement with a general down-throw of the eastern blocks. Exceptions with down-throw of the western side have been mentioned above, namely the faults in Vælddal and Segelsällskapets Fjord. Yet in the development of the block fault pattern it was important as well that repeated *rotation* occurred across and along the strike of the blocks. Moreover, in the coastal region of Wollaston Forland

[275]) H. BÜTLER (1957, pp. 44–50); J. PUTALLAZ (1961, pp. 78–80).

[276]) The term "*Vælddal fault*", introduced by J. PUTALLAZ (1961, pp. 68–70) supersedes the term "Bjørnedal fault" (D. T. DONOVAN, 1953).

[277]) *Cf.* J. HALLER (1958, pp. 136–38, 149).

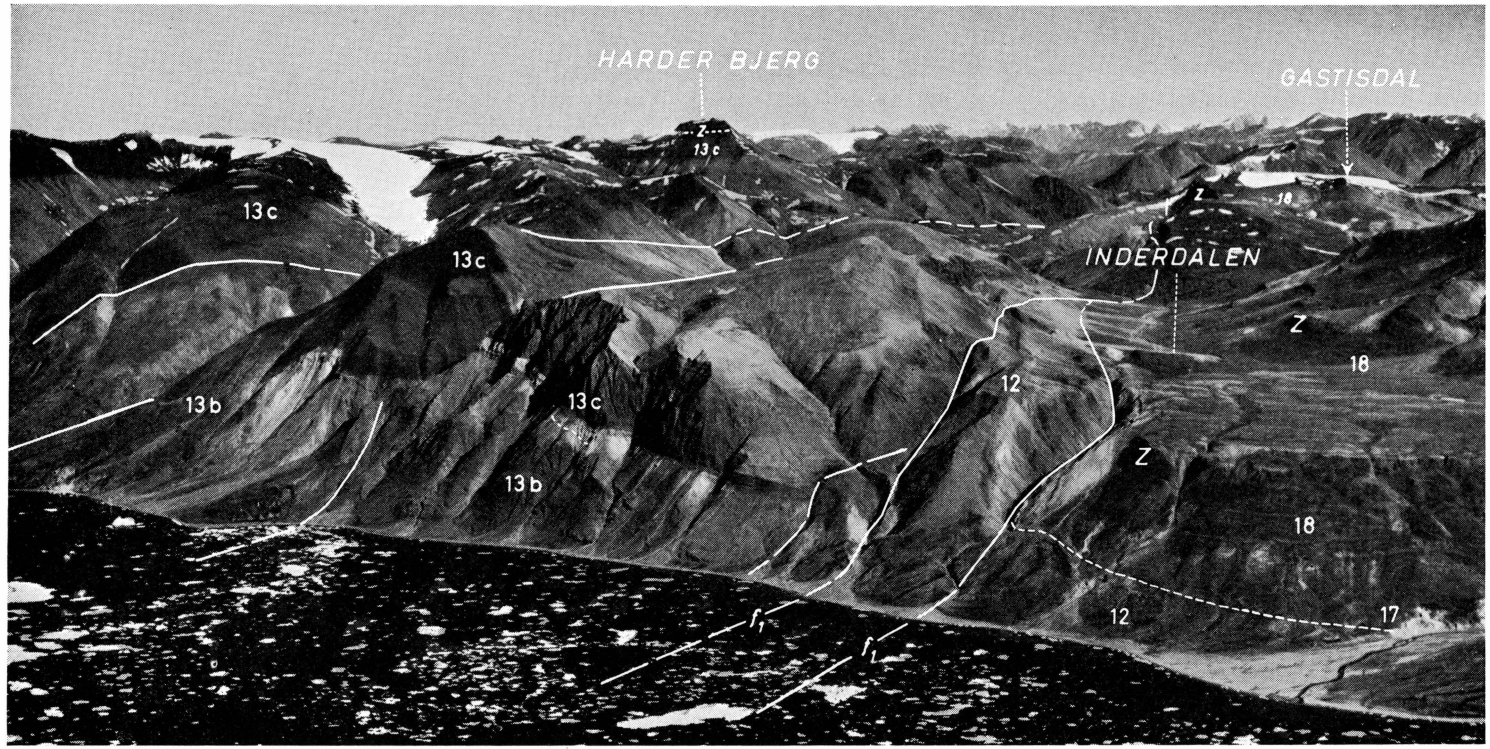


Fig. 82. Aerial view of southeastern Gauss Halvø with Kejser Franz Josephs Fjord in the foreground. The picture shows the trace of the "*post-Devonian main fault*" (f_1). This fundamental fracture zone came into play in Carbono-Permian time (cf. p. 137); it remained active throughout Mesozoic and Cenozoic times. The formations involved in this section are, Middle Devonian (*12*), Upper Devonian (*13 b* = Kap Graah Series, *13 c* = Mount Celsius Series), marine Upper Permian (*17*), Eotriassic (*18*), and Tertiary basalts (*Z*). Note that on the western highground, at the 1679 m high Harder Bjerg, the base of the basalts lies some 500 meters higher than east of the "main fault", where corresponding lava floods make up the flat-topped mountains between Gastisdal and Inderdalen (cf. H. Bütler, 1954, p. 122). In the lower corner right the mouth of Margrethedal is seen. — Air-phot. E. Hofer, 1950.

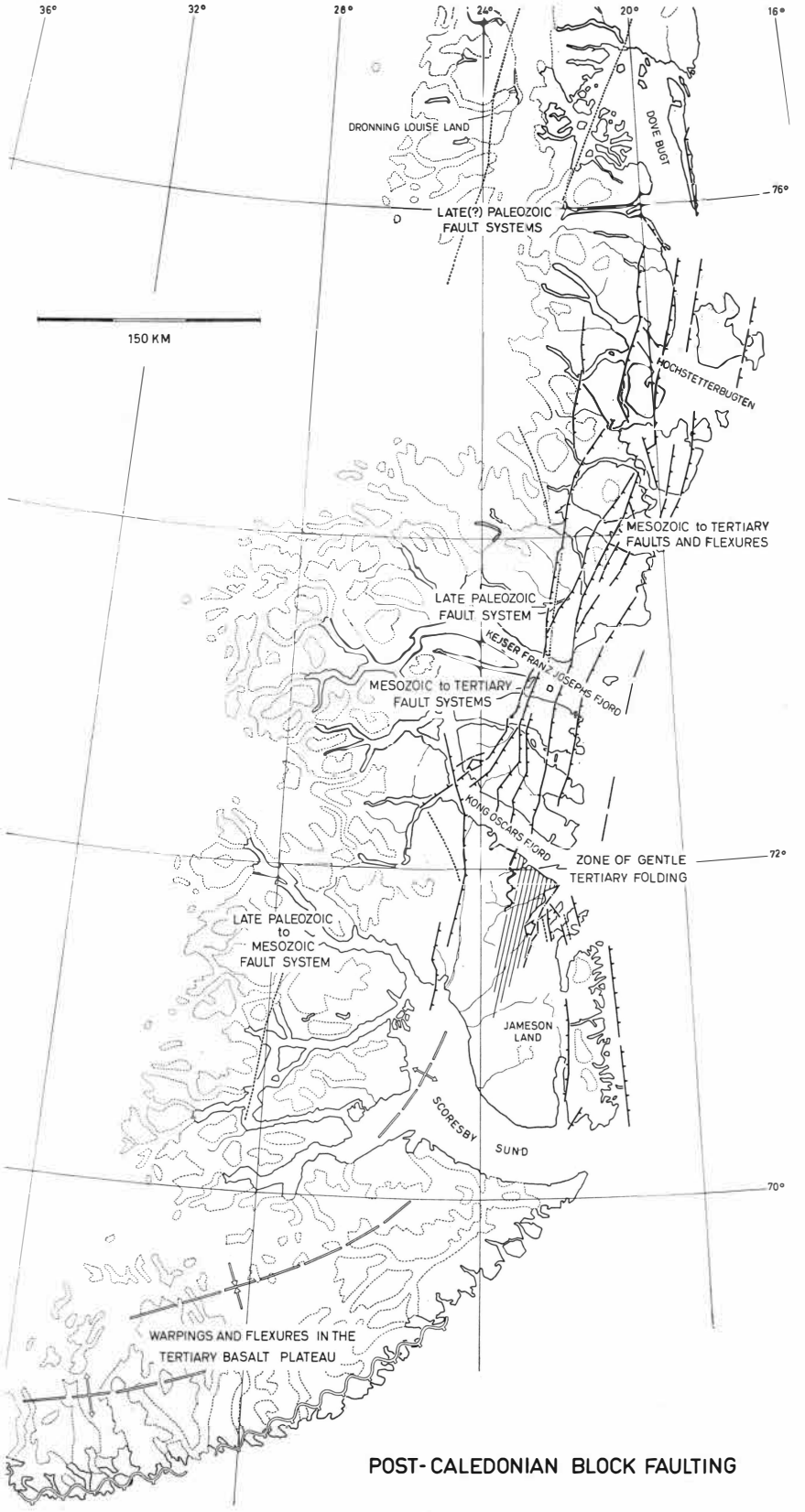

36°
32°
28°
24°
20°
16°
76°
72°
70°
DRONNING LOUISE LAND
DOVE BUGT
LATE(?) PALEOZOIC
FAULT SYSTEMS
150 KM
HOCHSTETTERBUGTEN
MESOZOIC to TERTIARY
FAULTS AND FLEXURES
LATE PALEOZOIC
FAULT SYSTEM
KEJSER FRANZ JOSEPHS FJORD
MESOZOIC to TERTIARY
FAULT SYSTEMS
KONG OSCARS FJORD
ZONE OF GENTLE
TERTIARY FOLDING
LATE PALEOZOIC
to
MESOZOIC
FAULT SYSTEM
JAMESON
LAND
SCORESBY
SUND
WARPINGS AND FLEXURES IN THE
TERTIARY BASALT PLATEAU
POST-CALEDONIAN BLOCK FAULTING

Fig. 83.

A. VISCHER[278]) observed that fault blocks previously tilted westwards were subjected to gentle eastward rotation in post-basaltic time (cf. Fig. 70).

South of the area covered by Map 3, in northeastern Jameson Land in particular, a zone of shallow *post-basaltic folding*[279]) is seen (cf. Fig. 83). The northerly trending folds have been launched apparently by vertical displacement of fault blocks. However, the fold structures proper—box folds with broad crests—were mainly brought about by *gravity sliding* and *décollement* caused by the Upper Permian evaporite succession (gypsum)[280]).

Cenozoic disturbances in Northeast Greenland

North of the 80th parallel a *shallow folding* including some thrusting affected the northeastern part of Kronprins Christian Land (see Map 1). Corresponding structures have as well been traced in the eastern part of Peary Land. The movements are assumed to be of Tertiary age and having involved all post-Caledonian cover rocks, which include Carboniferous, Permian, Triassic, Cretaceous and/or Tertiary. The latter ages refer to the 300 m thick succession of dark-colored marine sandstones at Nakkehoved[281]). From these beds a few bivalves were collected, recorded as *Barbatia* sp., *Nucula* sp., and *Yoldia* sp. Yet they are inadequate to date the formation. At Nakkehoved the beds dip 14° towards the southwest. Low dip values like this characterize the shallow fold structures indicated on the Tectonic Map. In the vicinity of Station North a *thrust system* has been observed. This is presumably related to the folding as well. It carries nonfossiliferous black shales including thin beds of dolomite (Hagen Fjord Group ?) upon Upper Paleozoic sediments, which, in turn, are rich in fossils.

In the central and southern parts of Kronprins Christian Land, the Caledonian nappe sheets have been slightly warped. Moreover, strike-slip displacement has been noted along some post-Caledonian NE-SW faults. There are also northwesterly running faults—evidently of rather late date—such as the transverse fault extending from Posten (Hekla Sund) to Centrumsø. It is possible that these features too were brought about by Tertiary movements.

[278]) A. VISCHER (1943, pp. 124–25, 165).
[279]) A. ROSENKRANTZ (1929, p. 149); A. NOE-NYGAARD (1934, p. 76).
[280]) R. TRÜMPY and K. GRASMÜCK (in press).
[281]) E. NIELSEN (1941, pp. 28–32).

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